Groundwater variability across India, under contrasting human and natural conditions

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Key Points:

- Characterized the hydrological and socioeconomic divergence associated with groundwater irrigation in India.
- North India's most productive aquifer experiences severe groundwater depletion under changing climate and policy interventions.
- South India's water demands and policies could engender a socioeconomic crisis, whereas natural ecosystems exhibit exemplary resilience.

Abstract

Characterizing local to regional scale water cycles and water resources will be crucial for achieving the United Nations' water-related Sustainable Developmental Goals. However, quantification and understanding of groundwater extraction across scales have been hampered by inadequate water usage reporting and limited information on irrigation practices. Here we analyze observations from ~15,000 groundwater monitoring wells and the Gravity Recovery and Climate Experiment (GRACE) satellites together with irrigation, agricultural, and meteorological datasets to show how drought-induced coupling between natural and anthropogenic groundwater storage variations has caused sustainability challenges in India, the world's biggest consumer of groundwater for irrigation. Notably, the mechanisms and consequences of such coupling differ significantly depending on aquifer types. In Andhra Pradesh's hard rock aquifer, groundwater declines have been limited, despite the nearly constant water scarcity that its farmers face. Moreover, it's free farm power policy involves an annual irrigation energy (mostly coal-based) consumption of 26 billion kWh that costs US$ 2.5 billion, possibly unparalleled compared to any other part of the world of similar size (0.27 million km^2). In West Bengal's highly permeable alluvial aquifer, the water table is declining rapidly (15 cm/yr) due to a policy that encourages irrigation. Situated between these two states, Odisha's aquifer shows substantial resilience to drought, owing to the state's relatively natural landscape and forest restoration policy. The findings of this study provide new insights to understand the divergent aspects of groundwater irrigation in north versus south India, which can enable development of adaptation and mitigation strategies to avert the looming water crisis.

Plain Language Summary

Groundwater is a vital resource in regions where rainfall is inconsistent or surface waters are inadequate to meet agricultural, industrial, and municipal/domestic needs. In many parts of the world, groundwater levels are declining due to massive withdrawals to support irrigated agriculture. The problem is compounded when drought strikes and policies do not incentivize water conservation. Such has been the case in India. In fact, India is the world's biggest consumer of groundwater for irrigation. However, India is not uniformly afflicted by groundwater depletion, and this study aims to understand why. We find that groundwater variability and the interactions between human and natural conditions are largely controlled by the aquifer type. In fact, farmers in south India are more prone to climate variability on an interannual scale, relying on rainfall every year to replenish the thin hard rock aquifer. In turn, farmers in north India extract the currently reliable but not sustainable static groundwater stored in the thick alluvial aquifers. This difference necessitates distinctive groundwater management plans to ensure resilient agriculture, deemed the economic backbone of the country.

1. Introduction

Groundwater resources support socioeconomic welfare and environmental sustenance worldwide, and protecting them will be critical for India to meet the societal needs of a rising population (~1.3 billion) (Gleeson et al., 2012). Known as a hotspot of groundwater storage (GWS) depletion (Panda & Wahr, 2016; Rodell et al., 2009; Tiwari, et al., 2009), India has expanded its groundwater-fed irrigation into the unsuitable hard rocks of semi-arid south India. Particularly, the twenty-first century drought-driven aridity, as captured in regions where rainfall is counterbalanced by high evaporative demand through low aridity index (AI) (Huang et al., 2016) (see supporting information Figure S1), has unfolded unique challenges. In fact, the pervasiveness of aridity has forced farmers to drill millions of deep wells (GOI, 2017) as an adaptive strategy, resulting in climate-induced indirect impacts (Taylor et al., 2013). In general, as the arid regions grew complementing the drying phase since the 1980s (Singh et al., 2014), the groundwater irrigated area using tube well rose by 23 million ha, whereas the traditional surface irrigation through canals declined (Figure S1). Consequently, the agriculture energy consumption has jumped by more than twenty times, with the current requirement of 199 billion kWh (kilowatt-hour) (Figure S2) that accounts about one-fifth of the country's total electricity use. A significant proportion of it can be attributed to groundwater depletion (Mishra et al., 2018).

However, among the cascade of its compounding effects, the most disheartening issue is the rising rate of suicides of smallholders (Carleton, 2017; Maréchal, 2009). By contrast, although deep well drilling in response to a similar trajectory of droughts in the US (the second largest groundwater user) has been acknowledged as an unsustainable stopgap, its expected social impact is largely confined to widening wealth inequality (Perrone & Jasechko, 2019). Globally, much of our knowledge of ongoing groundwater depletion and future projections is based on estimation of groundwater storage (GWS) trends. However, analysis of Gravity Recovery and Climate Experiment (GRACE) satellite (Tapley et al., 2004) mass change observations and in-situ water table depth (WTD) measurements indicate that trends are not only sensitive to the spatiotemporal scale of analyses, but they are also confounded by the non-uniformity of monitoring wells (i.e., shallow versus deep) which complicates development of policy guidance (Alley et al., 2018; Brookfield et al., 2018; Hora et al., 2019; Russo & Lall, 2017). This is particularly true in India where the scale effect (Alley et al., 2018) is enormous, as captured in major groundwater irrigated state's agriculture pump connections and energy use (Figure S2). As such, improvement in water management efficiency at the district scale is essential for food security in India (Davis et al., 2018; Joshi et al., 2021). But neither GRACE data nor the shallow-well dominated (>80%) monitoring network appear sufficient to provide the needed information.

In this backdrop, sustainable management of groundwater resources demands a detailed understanding of complex human-natural system interactions (van Loon et al., 2016; Vogel et al., 2015). Especially so given the groundwater recovery paradox in south India that hardly complements the governing social crisis (Hora et al., 2019). To this end, we examine the interlinkages of hydrological, socioeconomic and environmental signatures and ensuing sustainability challenges at different spatiotemporal scales. First we review state-mandated groundwater practices and policies, but critically compare the states of undivided Andhra Pradesh (AP), West Bengal (WB) and Odisha (Figure S2) that represent contrasting farm-power policies,

land-use change, climate and hydrogeology. Specifically, AP is in a semi-arid region underlain by a hard rock aquifer, and it has experienced both a deep well revolution and an explosion of smallholder suicides (Llamas and Martínez-Santos, 2005; van Steenbergen, 2006). WB exemplifies how policy modifications can create an even greater crisis despite access to a productive alluvial aquifer (Gleeson et al., 2012). Odisha, which remains a largely natural ecosystem, illustrates a promising conservation strategy (Mehrabi, et al., 2018). We hope that these lessons will lay the foundation for the policy and governance needed to meet multiple United Nations Sustainable Development Goals (SDGs) (Guppy et al., 2018).

2. Data and Methods

In-situ groundwater levels from more than 15000 observation wells during 1996-2016 forms the basis of investigation, which was obtained from the Government of India's Central Ground Water Board (CGWB). CGWB records water table depths (WTD, meter below ground level) typically for the months of August, November, January and May to represent the monsoon, post-monsoon, winter and dry seasons, respectively, in a hydrological year (June to the succeeding year May). As addition or abandonment of wells is intrinsic to any monitoring system, there are considerable missing observations. Thus, screening of wells on the basis of data continuity to capture point scale (i.e., well specific) trends greatly reduces the spatial representation, which is again constrained by contrasting trends from shallow versus deep monitoring wells (Hora et al., 2019). We, therefore, assess the mean and quantiles of WTD over different spatial domains to explain the natural and human dimensions, particularly the agricultural and irrigation policies that are implemented at the state or district scale. Wells with less than 60% of observation are excluded from the analysis. Moreover, we analyse the regional (north versus south India) WTD with respect to well types (i.e., shallow dug wells and tube wells) and highlight the most impacted representative states. To ascertain consistency and precision of scale effects, the district scale WTD trends were compared with irrigation, agriculture, and other related components of irrigation.

To understand the varied pumping effects in diverse hydrogeology, we use the recent enumeration of active as well as dry wells during 2006-2013, from the Minor Irrigation Census report (GOI, 2017). In absence of pumping data that prevents segregation of human stress, this data set, classified with respect to dug well (DG), shallow tube wells (STW, <35 m), medium tubewell (MTW, 35-70 m) and deep tube well (DTW, above 70 m) (GOI, 2017), provides at least indications of human intervention. Moreover, to understand the scale (spatial) effect of groundwater use, we derive the percentage of total land area equipped for groundwater irrigation from the latest Global Map of Irrigation Areas (GMIA) (Siebert et al., 2013) and the groundwater development (ratio of annual groundwater extraction compared to availability, %) from CGWB. Additionally, the district-scale irrigated area from different sources (dug well, canal, tube well) and also the major cropped area, compiled by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), were used for the description of land-use change and irrigation transitions.

We analyze rainfall, the primary source of groundwater recovery, to identify meteorological stresses and also to model its impact on WTD changes, for which the daily gridded data at 0.25° is obtained from Indian Meteorological Department (IMD). Particularly, to evaluate the aridity index (AI, ratio of rainfall to PET), the modelled PET from the Global Land Evaporation

Amsterdam Model (GLEAM) (Martens et al., 2017) is used. To understand the drought persistence and its impact on groundwater, the 12-month standardized precipitation evapotranspiration index (SPEI, modelled by water demands through evapotranspiration and rainfall supply) (Vicente-Serrano et al., 2010) is found appropriate. In-situ WTD trends are compared with the satellite-based groundwater storage (GWS) changes, for which the monthly Gravity Recovery Climate Experiment (GRACE) records during 2002-2016 is used. Particularly, from the GRACE-based terrestrial water storage (TWS), we derived GWS by subtracting the surface water storage component of the hydrological cycle, comprised of soil moisture, snow, and canopy storage. But, given the lack of large-scale time series observational data on these components, it is derived from the Noah land surface model of the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004). Although several GRACE products are available, for consistency with the previous studies (Asoka et al. 2017; Hora et al., 2019), we use the Centre for Space Research RL05M mascon solution, which is parameterized for minimizing leakage errors (Save et al., 2016).

Owing to non-normality of hydroclimatic data in presence of outliers (extreme events) and short time series, we consider the non-parametric Mann-Kendall test for trend analysis, whereas the rate of change is quantified based on the Sen slope estimation method (Helsel et al., 2020). Application of this method to WTD (Asoka et al. 2017; Hora et al., 2019; Russo & Lall, 2017) is particularly important because of intrinsic aberrations from human error in recording data and sensitivity of open well to episodic rainfall or excess human extraction. To address the biases from well selection (Hora et al., 2019), we assess trends in mean and quantiles of WTD, such as the 25th, 75th and 90th percentiles, that can capture the differential response of varied well depths. Especially, due to the lack of representative deep monitoring wells, the 90th percentile can partly reflect the pumping effect that otherwise gets confounded within the mean response. The null hypothesis of no trend is tested by the two-tailed 0.05 significance level ($p<0.05$). Moreover, the locally weighted scatterplot smoothing (LOWESS) (Cleveland, 1979) is applied for visual comparison of patterns and turning points in time series. Widely applied in hydrologic time series (Lall & Sharma, 1996), LOWESS is a robust, locally weighted linear regression technique to fit flexible curve between two variables based on conditional expectation.

We perform Empirical Orthogonal Function (EOF) analysis, which identifies the predominant spatial and temporal patterns by means of decomposition (Güntner et al., 2007), using the seasonal in-situ WTD during 1996-2016. Using correlations between the leading EOF mode and the SST over the Indian Ocean. the role of large-scale climate variability on groundwater is evaluated. To this end, the National Climatic Data Center's Extended Reconstructed SST (ERSSTv3b) (Smith et al., 2008) is used. To model the relationship between the local rainfall and WTD, the vector autoregression (VAR) impulse response function, is employed, whereas the causal relationship is assessed using the Granger causality test. A detailed description of these methods is given by Russo & Lall (2017).

We also calculate the farm power energy use and its carbon footprint using information from different sources (e.g., socioeconomic survey reports). Considering the carbon dioxide (CO_2) emission of ~ 0.85 kg per kWh of energy generation (Raghuvanshi et al., 2006), the total emission from the country's agricultural consumption is estimated to be ~169 million tons. However, it is important to note that the Minor Irrigation Census report informs about the registered wells only, whereas the state government's expenditure and related statistics on farm power consumption

supplement more crucial information about the anthropogenic component when pumping data is scarce globally. For example, as per the latest socioeconomic survey report (GOAP, 2016) and also from the government's press notes, the total number of agricultural pump connections in undivided AP is found to be 4.02 million, more than the census report (Figures S2 and S3). This entails an energy consumption of 26 billion kWh annually, each connection at the rate of 6542 kWh. Assuming the power supply cost of ~ US$ 0.097 per kWh during 2012-13 (GOI, 2014), AP's free power policy incurs a financial burden of ~ US$ 2.5 billion, the largest among the Indian states.

3. Results and Discussion

3.1 Uncertainties and Limitations of Groundwater Level Trends

Figure 1 illustrates the scale effect of groundwater irrigation and depletions in diverse hydrogeological settings in India. Noteworthy is the expansion of groundwater irrigation into the hard rocks of semi-arid south India (Figures 1a and 1b). Although the groundwater development metric (ratio of extraction to availability) has captured the district-scale hydrological stress more prominently in the most arid northwest India (Figure 1c), the environmental stress in south India is distinguishable from the disproportionately high pump sets, energy use, and deep tube wells (Figures S2 and S3). Consistent with the previous studies (Dangar & Mishra, 2021; Panda & Wahr, 2016; Rodell et al., 2009; Tiwari, et al., 2009), GRACE observed large scale water storage losses in the Indo-Gangetic alluvial aquifer of north India (Figure 1d) during 2002-2016. Whereas the district-averaged WTD trends from in-situ observations during 1996-2016 revealed significant (p<0.05) declines in 40% of the 556 districts compared to rises in 7% (Figure 1e), appreciably matching the scale effects of groundwater irrigation and aridity. During 2002-2016, however, WTD rises can be seen in large parts, identifying significant declining trends in 23% of districts only (Figure 1f). This turnaround is inconsistent with how the aquifer would be expected to respond to an aridity-driven increase in groundwater extractions through unscrupulous digging of deeper wells (Figures S1-S3).

All the agriculturally important states except WB receive free or subsidized power, which incentivizes groundwater pumping (Shah et al., 2012). So, for the south Indian states of AP, Karnataka and Tamil Nadu, the rising WTD trend during 2002-2016 appears very unlikely (Figures 2a and 2b), given their high energy consumption and irrigation well frequency (Figures S2 and S3). In turn, all the north Indian states (except Rajasthan) expectedly show declines. With respect to the paradoxical WTD trends of north (above 23º N) versus south (below 23º N) India (Asoka et al. 2017; Hora et al., 2019), a stark contrast is observed within and between dug well and tube well observations that can have masking effects (Figure S4). As such, the preponderance of shallow dug wells complicates the interpretation of mean WTD across the county. Still, both dug wells and tube wells of south India are much shallower than that of north India (Figure S4). This suggests deep aquifers in north India are relatively better sampled to capture the effects of pumping compared to south India. Irrespective of well types, the mean WTD in north India has been declining three-times faster (10 cm/yr) than south India during 1996-2016. The rising water-level in dug wells seems to have offset the declines in tube wells in south India, leading to weakening or even reversal of trends during 2002-2016. However, the relative magnitude and spread of declines in the 90th percentile irrespective of study period (Figures 2c and 2d) appear

more representative of farmers' deep pumping wells in different states. Even in the country's depletion hotspot of Punjab and Haryana, the 90th percentile is dropping at a two-times faster rate (96 cm/yr) than the mean WTD.

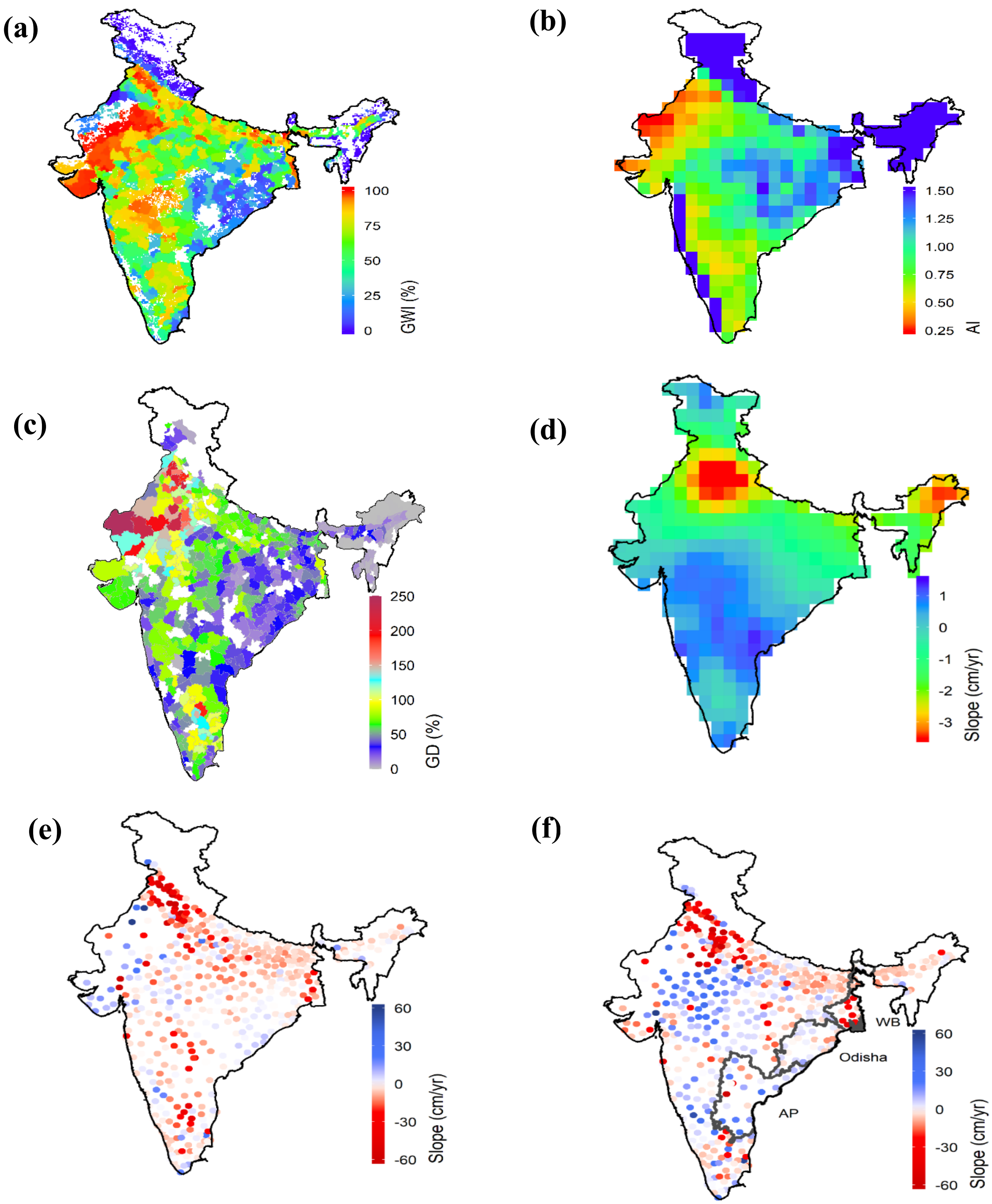

Figure 1. Interlinkage of groundwater irrigation, climate and depletions in India based on (a) the map of percentage of land area equipped for groundwater irrigation, from the latest Global Map of Irrigation Areas (GMIA), (b) the aridity index (ratio of annual rainfall to potential evapotranspiration) and (c) district scale groundwater development (stress indicator pointing the percentage of annual extraction with respect to available resource from recharge). (d) Trends from GRACE records during 2002-2016 and its comparison with that from district-averaged in-situ water table depth (WTD) (represented by centroids) during (e) 1996-2016 and (f) 2002-2016. The states compared critically (AP, WB and Odisha) are shown.

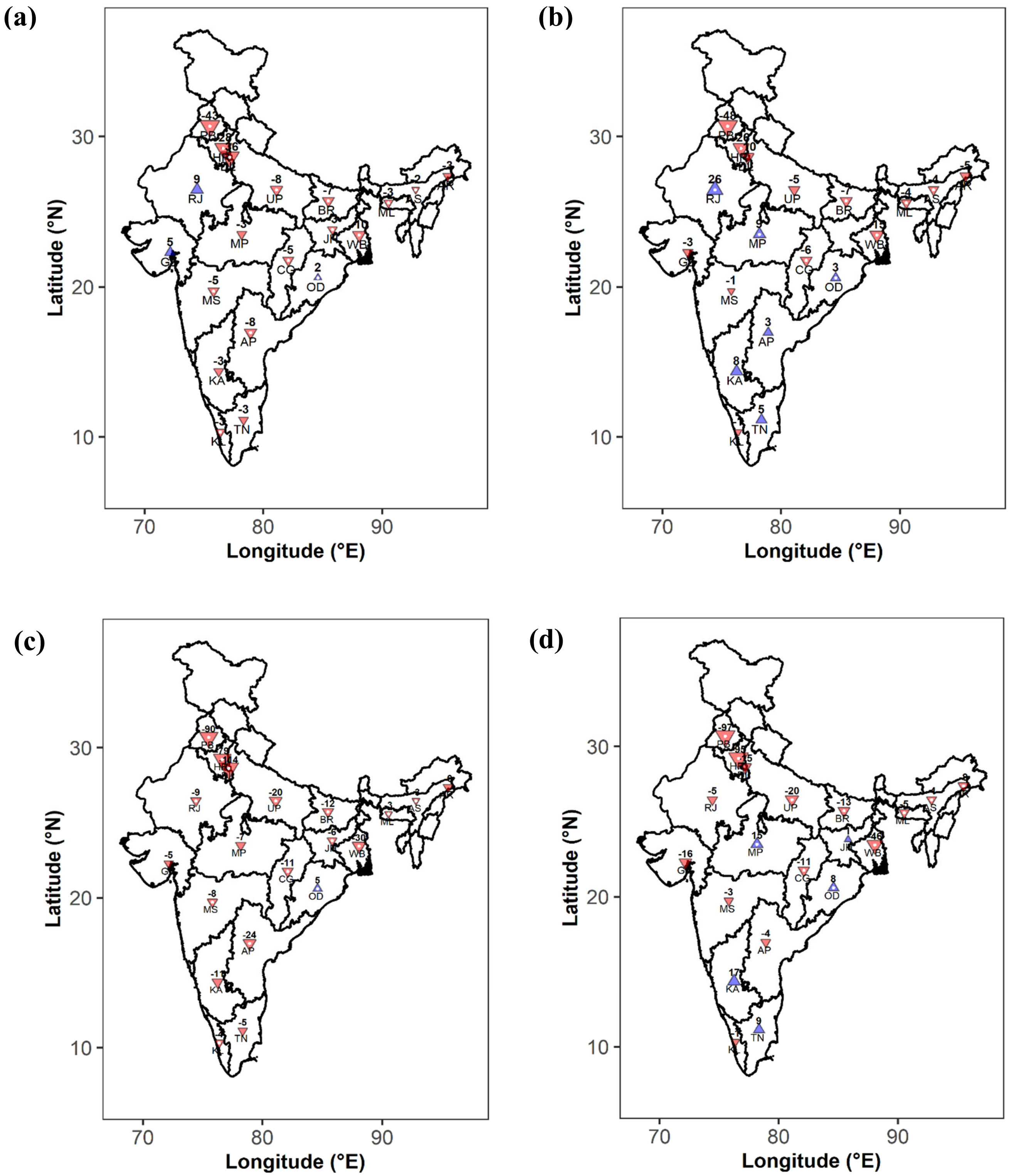

Figure 2. Map of trends (inset, cm/yr) in the state-averaged mean WTD during (a) 1996-2016 and (b) 2002-2016. The maps (c)-(d) are same as (a)-(b), but for the 90th percentile. The states pointed in the maps are: Andhra Pradesh (AP), Tamil Nadu (TN), Karnataka (KA), Punjab (PJ), Haryana (HR), Rajasthan (RJ), West Bengal (WB), Odisha (OD), Gujarat (GJ), Uttar Pradesh (UP), Madhya Pradesh (MP), Maharashtra (MS), Kerala (KL), Bihar (BR), Jharkhand (JH), Chhattisgarh (CG), Meghalaya (ML), Assam (AS) and Arunachal Pradesh (AR).

The multi-layered aquifer system in India, characterized by recharge and extraction processes that varyon scales as small as a few kilometers, exerts considerable control over water storage variability (De Graaf et al., 2015; Joshi et al., 2021; van Dijk et al., 2016).The flat and porous soil of the Ganges Plain is not conducive to surface water storage (Revelle & Lakshminarayana, 1975). Consistently, we find north India to have 622 reservoirs only (CWC, 2019), which is one-third of that enumerated in south India in 2016, though both the regions have witnessed a nine-fold rise since 1981 (Figure S4). The subsurface component has also responded distinctively to anthropogenic and climatic factors, as implied from the slump and recovery patterns of WTD in certain states (Figure 3). The locally weighted scatterplot smoothing (LOWESS) regression displays conspicuous differences between the shallow (25th percentile) and deep (90th percentile) WTD variability, which likely reflects the dominance of rainfall and anthropogenic pumping effects in shallow and deep wells, respectively. Despite intense pumping, a dry-wet cycle of WTD has emerged in the southern hard rock dominated and relatively humid states of AP, Karnataka and Tamil Nadu (Figure 3). This is mainly because of an extreme dry spell during 2000-2004 (Kumar et al., 2011), causing dire water stress in the country that even flattened for the first time the fast rising energy consumption (Figure S2). Given the high density of reservoirs in south India (Figure S4), wet extremes thereafter during 2005-2007 (Kumar et al., 2011) generated substantial focused recharge (Asoka et al., 2018; Tiwari et al., 2011), leading to a fast WTD recovery. Conversely, pumping impacts accelerated by drought (Dangar & Mishra,2021; Mishra et al., 2016; Panda et al., 2021) outweighed the natural recovery process from rainfall in the northern alluvial aquifer, clearly reflected through monotonic drops. These effects are detected by GRACE; however, GRACE alone cannot distinguish storage changes at different aquifer levels (Girotto et al., 2017).

The rising GWS trend in south India is attributed to increased rainfall (Asoka et al., 2017), and the limited storage of its hard rock aquifer in any case could not sustain the sort of steep, persistent decline seen in the northern thick alluvial aquifer (Fishman et al., 2011). It should be noted that WB is endowed with the country's most abundant renewable groundwater (three-times more than AP). Yet, recharge from increased rainfall appears to be absorbed by the thick and permeable Ganges aquifer of WB, contrary to the fast replenishment and rise of WTD in the thin aquifer of AP. Similarly, in the thin aquifer of the desert of Rajasthan in northwest India (De Graaf et al., 2015), although the recent rainfall extremes should have raised its WTD, a stable pattern is observed because of aggregation that encompasses the overexploited northeastern thick alluvial aquifer (Figure 3). But, in Gujarat, despite distinctive WTD responses in its the alluvial, hard rock and desert regions (Panda et al., 2012), their aggregation resembles to that of AP. The only domain that exhibits exceptional recovery and resilience, especially considering the large-scale declines it experienced due to the 2002 drought (Panda et al., 2007), is the natural groundwater system of Odisha, relatively unaffected by irrigation. These analyses suggest assessment and interpretation of WTD trends from a relatively short time series require careful consideration, particularly with respect to south India's paradoxical recovery (Hora et al., 2019). Although it has been concluded that longterm trend analysis is not appropriate for hard rock aquifers (Hora et al., 2019), we describe below in detail how the district and state-aggregated WTD trends can reasonably be explained by a set of governing drivers, which in turn can inform future management decisions.

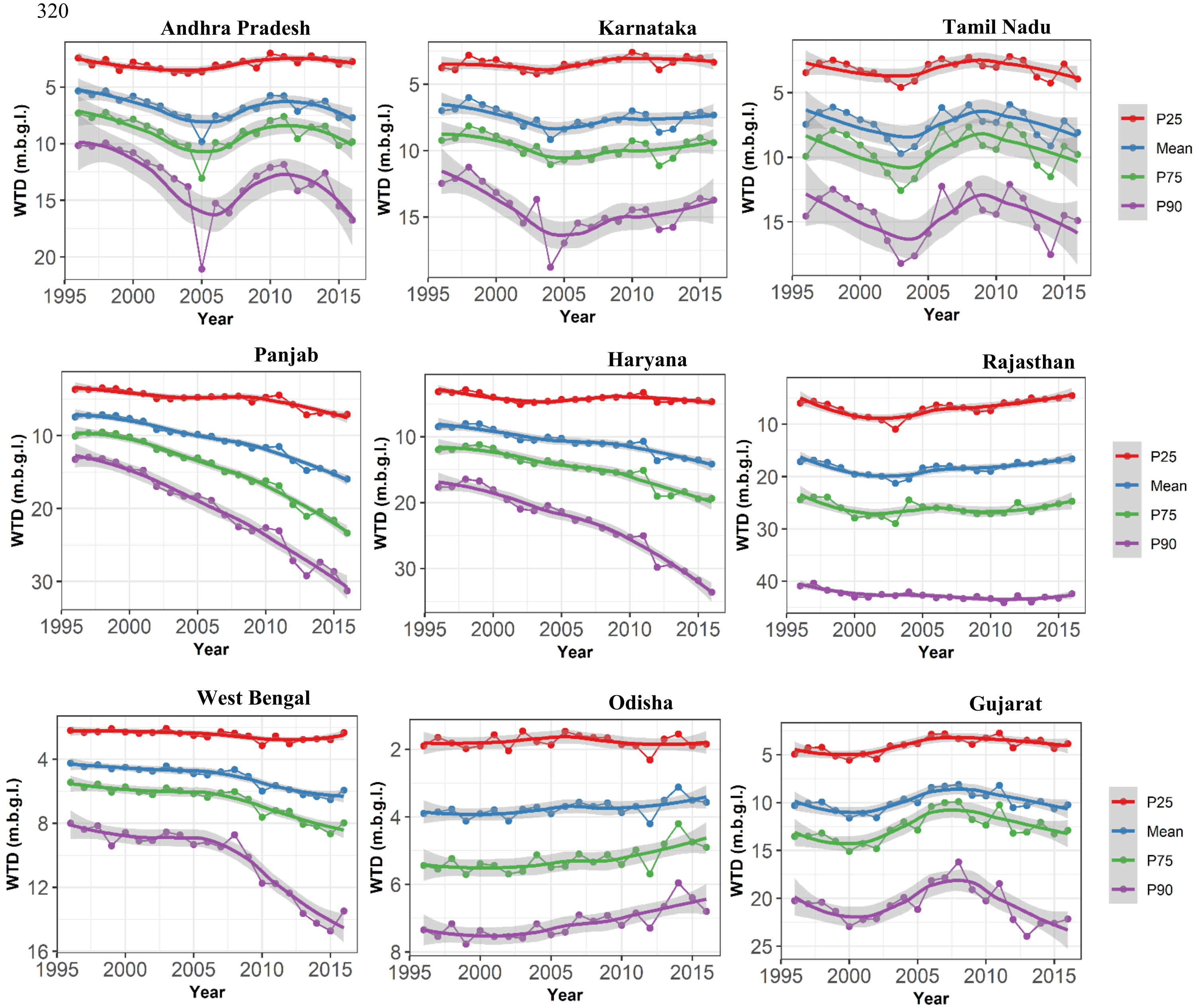

Figure 3. Temporal and vertical description of WTD, smoothed with the LOWESS regression and shaded with the 95% confidence interval, based on the 25th percentile (P25), mean, 75th percentile (P75), and 90th percentile (P90) of data for the representative states of India.

3.2 Drought and Society Feedbacks

Among the Indian states, the history of groundwater policy and irrigation practices in AP and WB since the 1970s provides important insights into the complexities of the human-natural

system (Figures 4 and 5, Table S1). The LOWESS regression suggests that surface water irrigation (canal and pond) was dominant, expanding rapidly during 1971 to 1990 (20,000 ha/yr, $p<0.05$), being supported by increased rainfall (Figures 5a and 5b). Thereafter, surface water irrigation suffered due to recurrent rainfall failures, indicating a transition from a wet to a dry phase. The annual mean streamflow at the Godavari river (the major source of surface water irrigation in AP) outlet gauging station, which correlates reasonably with rainfall (r =0.65, $p<0.05$), depicts declining flow from 1991 onward (Figure 5c). The failure of subsistence agriculture (Figure 5d) that engaged ~72% of AP's population was the primary reason that farmers began switching to wells as the source of water for irrigation, which also enabled the irrigated area to increase rapidly (77,000 ha/yr since 1991) owing to the ubiquity of groundwater (Figure 5a).

To reduce unscrupulous groundwater mining, the government of AP enacted the 'Water, Land and Tree Act, 2002'. Unfortunately, it coincided with the start of a drought and heatwave (2002-2004) that caused a terrible social crisis including a rash of farmer suicides (Bhadram et al., 2005; Taylor, 2013). This, in turn, prompted implementation of a free power policy in 2004 (Llamas and Martínez-Santos, 2005; van Steenbergen, 2006). Several states reeling under similar circumstances also justified the cause to implement free power policy. This spurred a competition among farmers to aggressively secure more water by sinking deep tube wells (Figure S3). At present, ~4 million agricultural pumps are operating in AP, jumping from ~2.3 million before the policy was implemented (van Steenbergen, 2006). This ushered in a massive land-use change (Figure 5d), as subsistence agriculture was replaced by cash crops with large water footprints. Smallholders became more vulnerable because their bets on expensive deep wells and cash crops often failed (Taylor, 2013), apparently due to the lack of buffering capacity of the hard rock aquifer during dry-hot events. There is a consistent correlation between the number of suicides in a district, faster LUC due to widespread drilling of new wells, and rapid WTD declines causing wells to go dry (Figure S5). The 90th percentile WTD decline, occurring at more than three-times (24 cm/yr, $p<0.05$) the mean during 1996-2016, indicates the severity of the situation. Within AP, the subregion Telangana (TG) stands out as the epicentre of the tube well revolution. Annually, it has added ~41,000 ha of groundwater-irrigated area since 1996, more than double that of the southwestern Rayalaseema (RS) and the canal-dominated coastal AP (CAP).

In WB, two things that seem to have galvanized groundwater usage after the 1970s (Figure 4b, Table S1) were the empowerment of smallholders through land tenancy reform (Banerjee et al., 2002) and rural electrification, which triggered a transition away from the diesel-powered irrigation beginning in the 1990s. As a result, summer season (Boro) rice cultivation expanded and water markets evolved, possibly because of fragmented landholdings, with a flat tariff on electricity usage. To address revenue losses and environmental concerns (mainly arsenic contamination from groundwater over-exploitation; Fendorf et al., 2010), the Groundwater Act of 2005 (requiring a license to pump groundwater) was passed. However, smallholder crises following large-scale droughts in 2009 and 2010 necessitated the abolition of licensing in 2011 (Jha, 2017). As a result, metered power connections more than doubled and substantial groundwater depletion was seen in districts where construction and abandonment (dry wells) of shallow tube wells occurred (Figure S5). Situated between these two heavily groundwater-irrigated states, AP and WB, the state with the least LUC, Odisha, has witnessed WTD rises in most of its districts, except in the north-east, which is influenced by WB's Boro rice cultivation (Figure S5).

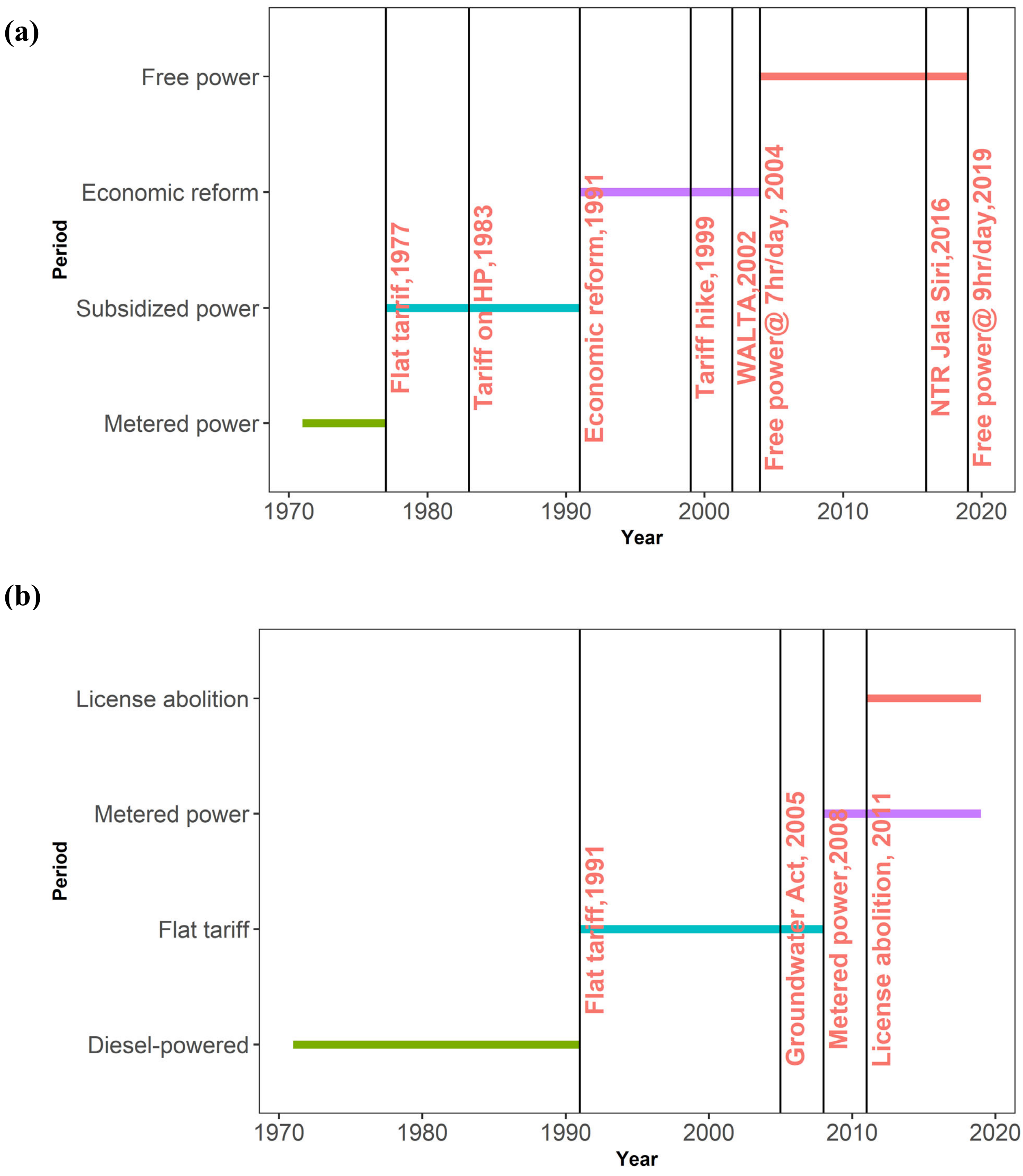

Figure 4. Timeline of major farm power and other policies associated with groundwater irrigation in (a) Andhra Pradesh (AP) and (b)West Bengal (WB) since the 1970s. Horizontal lines represent the major periods and vertical lines for year of policy implementation.

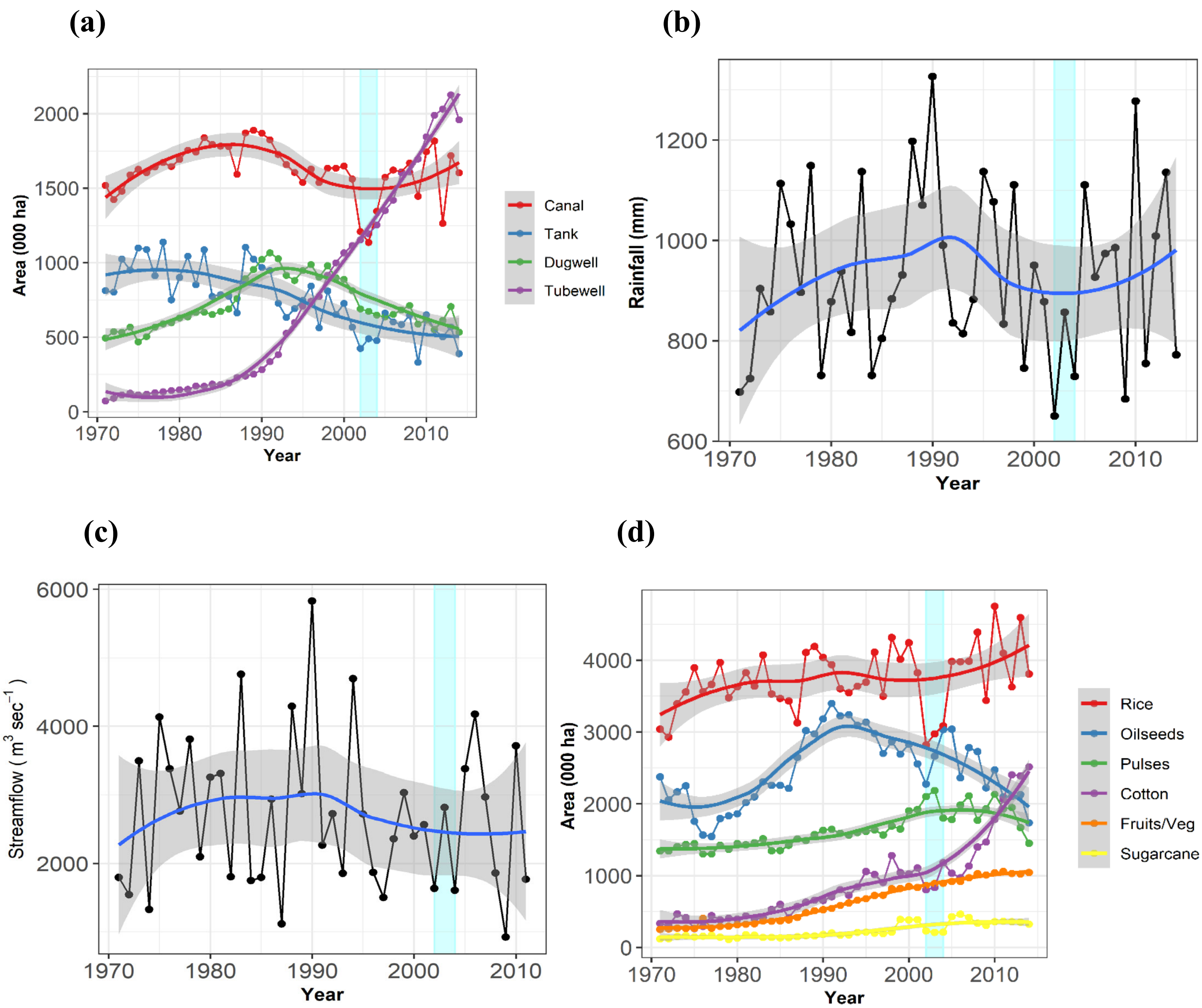

Figure 5. Transitions in human-natural system in AP through (a) irrigated area in response to changes in (b) rainfall and (c) streamflow since the 1970s. (d) The corresponding land-use change (LUC) for water-intensive crops. The marked years represent the 2002-2004 dryness that prompted the free farm-power policy. The embedded LOWESS regression reflects the temporal evolution.

The well-known 'turn of the century' droughts (Seager, 2007) that affected groundwater resources of the US (Scanlon et al., 2012) have fundamentally modified human-natural system interactions in India likely to have set in longterm depletions. High amplitude hydro-meteorological extremes may become the norm in a warming world, even without yielding systemic trends. But, diagnosis of aquifer dynamics is important for assessing system resilience.

To understand the associated recharge and discharge processes in terms of time-lag response and persistence, we compare the standardized seasonal WTD with the 12-month standardized precipitation-evapotranspiration index (SPEI, incorporates the consequences of high temperatures on drought) (Figures 6a and 6b). In AP particularly, large depressions in hydraulic head (i.e., cones of depression) were formed due to dewatering of the thin aquifer during the 2002-2004 dry-hot episode. This corroborates the concept of human-modified drought (van Loon et al., 2016). The associated baseflow reduction, conspicuously reflected in the dry-season 15, 30 and 45-day low streamflow (Figure 6c), may indicate the environmental limits of groundwater pumping (de Graaf et al., 2019). We find similar modifications but in different magnitude, in other heavily irrigated, hard rock dominated states, including Karnataka, Tamil Nadu and Gujarat. Remarkably, the simmering social crisis following this drought was alleviated by the subsequent capture (Konikow and Leake, 2014) of rainfall and streamflow via episodic recharge of the depleted aquifer.

Although the cyclic features seen in AP's hard rocks are not detectable in WB, Punjab and Haryana, the 2002-2004 dry spell certainly contributed to the persistent WTD decline observed in their thick alluvial aquifers (Figures 3 and 6a). On the other hand, the relatively natural hydrological system in Odisha experienced a clear transition to recovery after 2005 (Figure 6). This may be attributed in part to the successful implementation of the 2006 Forest Rights Act, which allowed forest dwellers the responsibility of sustainable conservation and the right to use forest products. In fact, Odisha was the most successful of the Indian states that allowed forest conservation through rural community participation (DTE, 2018). In spite of low spatial resolution, GRACE terrestrial water storage (TWS) anomalies capture the subregional distinction between hard rock and alluvial aquifer (Figure 6d). Nevertheless, most of the groundwater-irrigated states, irrespective of hydrogeology, are currently suffering from human-modified drought.

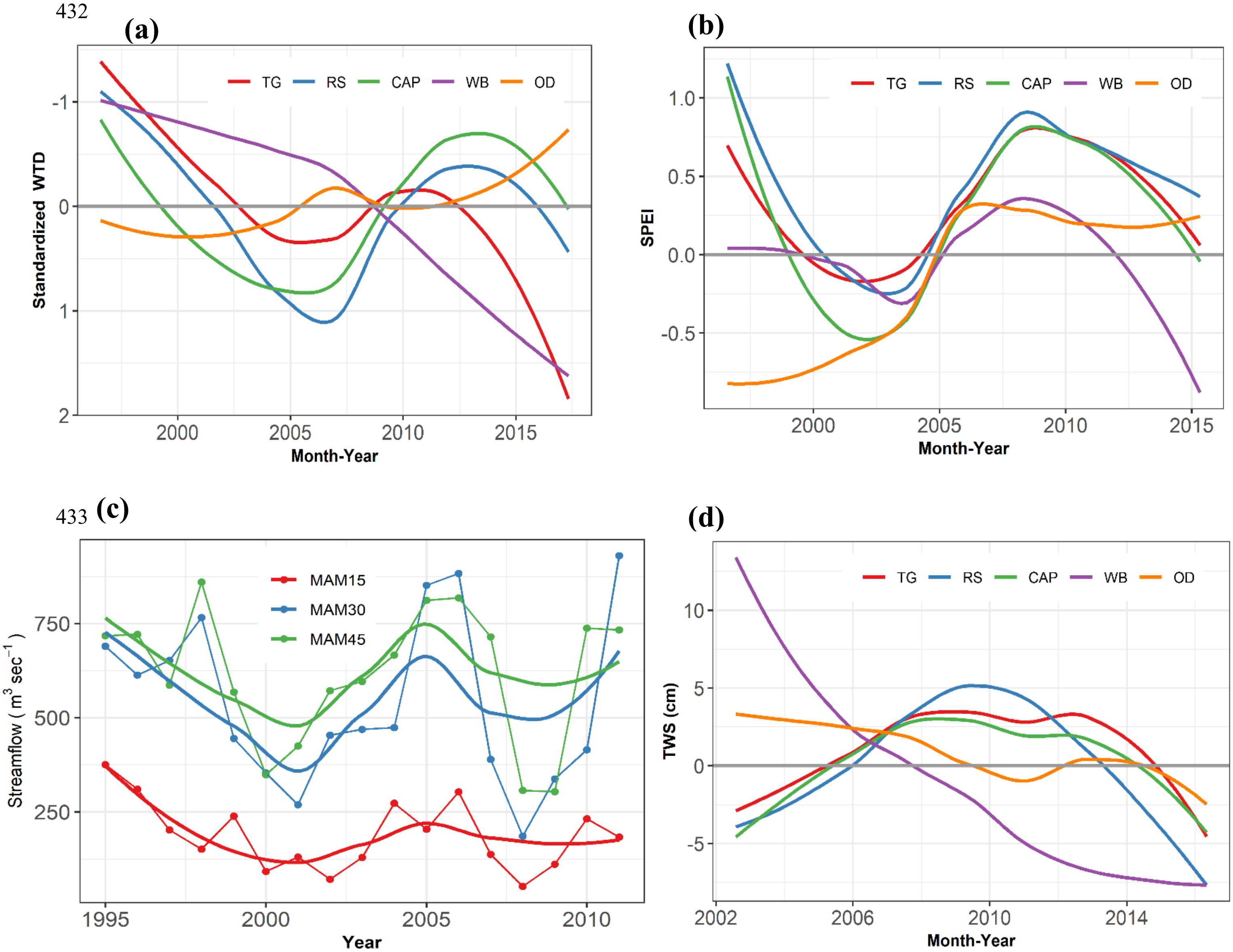

Figure 6. Hydroclimatic linkages based on (a) the standardized seasonal (i.e., August, November, January and May) WTD (LOWESS regression shown) in subregions of AP (Telengana (TG), Rayalseema (RS) and coastal AP (CAP)), West Bengal (WB) and Odisha (OD), and (b) the corresponding the 12-month SPEI (standardized precipitation-evapotranspiration index) expressed through (c) The non-monsoon summer season 15, 30 and 45-day minimum streamflow at the Godavari basin outlet, essentially sustained by baseflow, are largely affected by the human-modified droughts. (d) The seasonal terrestrial water storage (TWS) anomalies since 2002 consistently captures the differential aquifer response.

3.3 Influence of Climate Variability

It is well-known that large-scale climate variability modulates the monsoon rainfall of India, more significantly it's extreme events (Mishra et al., 2012; Roxy et al., 2015). It is, therefore, logical to understand how climate influences groundwater resources, that is obviously via rainfall. Empirical Orthogonal Function (EOF) analysis of GRACE GWS is shown to have captured the storage losses due to pumping through the leading mode of variability, which in turn is influenced by the Indian Ocean sea surface temperature (IO SST) (Asoka et al., 2017). We, however, find the EOF analysis of seasonal in-situ WTD decomposed into two orthogonal spatial patterns that enabled segregation of climate from the anthropogenic pumping effect (Figure 7). The leading EOF mode (EOF1) distinguishes the large monsoon-dominated central and eastern region from that of the arid northwest and southwest India (Figure 7a). The corresponding principal component (PC1), which explains 41% of the space-time variability, reflects the natural monsoon recovery and non-monsoon drawdown processes. EOF1 can be linked to IO SST variability, as evidenced by its high correlation with PC1 (Figure 7e). This linkage suggests that in-situ groundwater levels may be useful for assessing hydrological changes associated with decadal climate variability, the manner rainfall is employed (Roxy et al., 2015). Noticeably the modest downward trend in PC1 suggests large-scale climate drives the broad WTD variations. In particular, the 2002-2004 drought coincides with an anomalous SST warming over the western IO (Figure 7f). A slight pause in SST warming during 2005-2008 (subtle plateau in the LOWESS regression) corresponds with ample rainfall and consequent WTD rises. The second EOF mode (EOF2) (Figure 7c) mostly resembles the observed spatial pattern of WTD trends (Figure 1e). The corresponding PC2, accounting for 13% of WTD variability, exhibits a steady decline (Figure 7d), as observed in many human-dominated aquifer systems.

Our results suggest that seasonal and interannual groundwater storage changes (neglecting longterm trends) are controlled more by climate variations than by pumping, as also observed in the US (Russo & Lall, 2017; Thomas & Famiglietti, 2019). EOF1 also identifies a part of south India where groundwater levels are explained better by pumping effects (Figure 7a), in addition to the previously identified pockets of north India (Asoka et al., 2017; Malakar et al, 2021). But, even in the most depleted northwest India, rainfall is found to have indirectly influenced pumping effects (Asoka et al., 2017). We also emphasize the twenty-first century surge deep drilling that both the leading countries, India and the US, have adopted is fundamentally the indirect effect of drought. However, as pointed out by Russo & Lall (2017), lack of data on groundwater pumping is a critical limitation to segregate them.

Instead, groundwater response to hydroclimatic forcing is modelled using both vector autoregression (VAR) and the Granger causality test. Consistent with what Russo & Lall (2017) observed, the VAR model coefficients and the impulse response indicate that seasonal WTD is significantly (p<0.05) influenced by rainfall variations within the first year (Table S2, Figure S6), irrespective of well type. Moreover, the Granger causality test confirms that rainfall causes water table changes (p<0.05). Still, pumping effects in sub-regions of AP are reflected in model parameters and performance measures (e.g., R^2, coefficient of determination). Notably, WTD in Odisha, where human impacts are minimal, corresponds almost perfectly with rainfall variability (R^2 =0.93). Although its hard rock dominated geology might suggest a lagged response, it seems the predominant forest cover (Tian et al., 2014) facilitates rapid transmission of rainfall to the

aquifer. Similarly, the high correlation between rainfall and WTD in WB (R^2 =0.87) is evidently due to a rapid rate of recharge. WTD in both WB and Odisha displays a strong linkage with the western IO SST (r=0.75), implying the relative influence of large-scale climate via rainfall (Asoka et al., 2017). Corroborating the observed district scale depletion (Figure S5), the trend in the VAR model is significant (p<0.05) for both TG of AP and WB. Additionally, we modelled WTD with respect to the aridity index, to ascertain whether the temperature effect therein changes the model output. Results confirmed the greater role of rainfall variability.

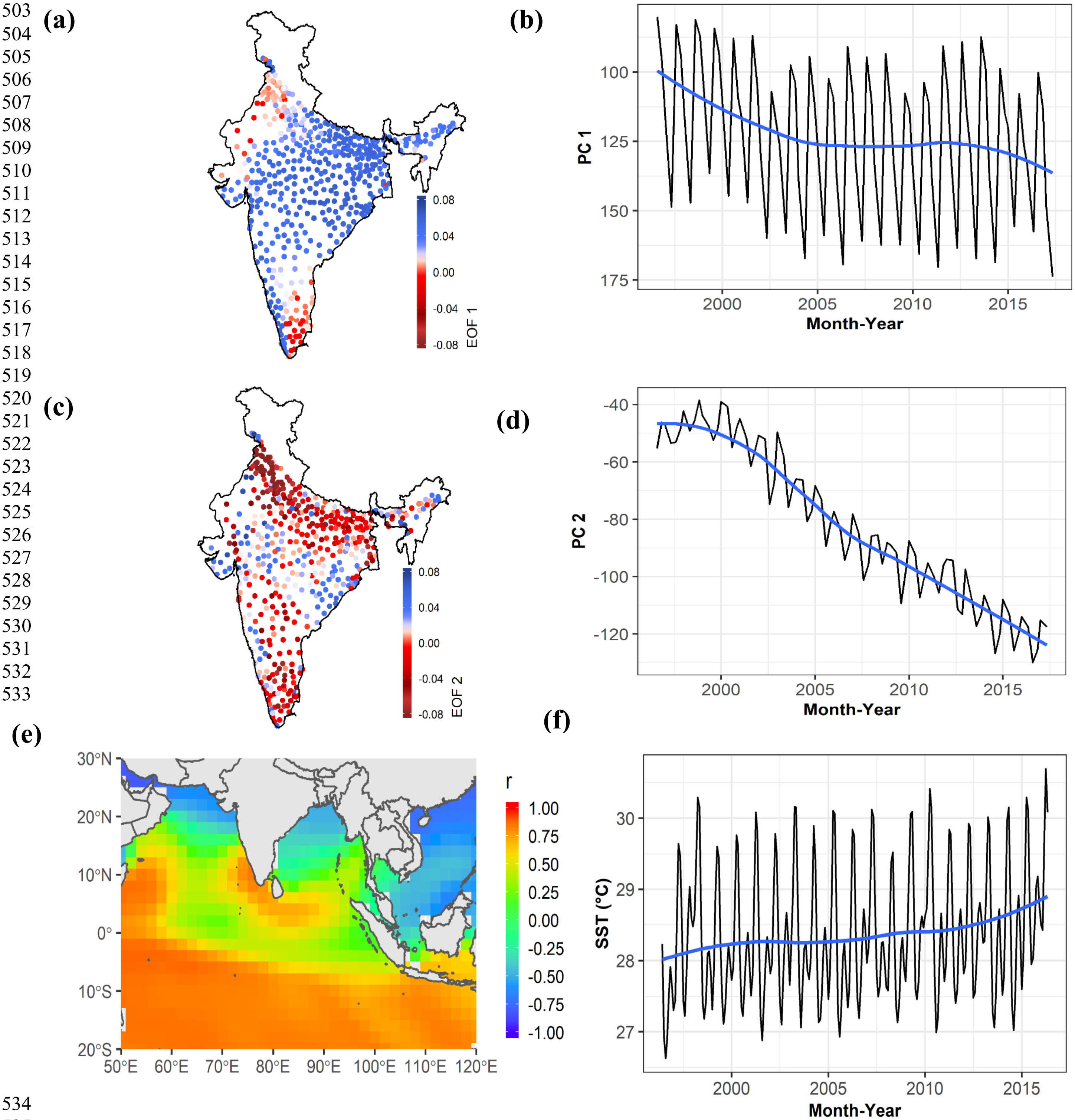

Figure 7. Empirical orthogonal function (EOF) analysis of the seasonal (monsoon, post-monsoon, winter, summer) WTD during 1996-2016 shows (a) the leading mode (EOF1) of variability and (b) the corresponding principal component (PC1). (c)-(d) same as (a)-(b), but for the second mode (EOF2) and PC2. (e) Impact of the Indian Ocean SST on groundwater levels reflected through the spatial distribution of correlation coefficients between PC1 and SST over Indian Ocean and (f) through the time series of seasonal SST over western Indian Ocean.

3.4 Hydrological Versus Socioeconomic Signatures

North India's alluvial aquifer is identified as the world's most depleted aquifer (Gleeson et al., 2012), but we argue here that socioeconomic and environmental stresses in south India's hard rock aquifer engender a situation that is even more precarious. Comparing the two is complicated by the different hydrogeological conditions, spatiotemporal patterns of depletion, and human interventions (Figures S2-S4). Chronologically, north India's groundwater irrigation began earlier; it started in the mid-1960s at a large scale particularly in the northwestern states of Punjab, Haryana, and Rajasthan through the massive crop intensification programme, known as the Green Revolution, which triggered land-use changes and unsustainable groundwater usage (Joshi et al., 2021; Panda et al., 2021; Rodell et. al., 2009; Tiwari et al., 2009; van Dijk et al., 2020). Still, to evaluate our hypothesis, we compared the most vulnerable representative states, Punjab (north) and AP (south). WTD declined by 43 cm/yr (p<0.05) in Punjab during 1996-2016, about five-times faster than in AP. However, comparison of energy consumption under the free power policy (an unbiased, indirect proxy for groundwater pumping) indicates that AP spends about US$ 2.5 billion annually on pumping, which is more than double of what Punjab spends. Circumstances are similar in other hard rock dominated states in south India, likely due to the predominance of deeper wells (Figures S2 and S3) that require more power to pump the same quantity of water.

Moreover, the environmental repercussions of agricultural expansion (Figure 5d) in AP are exemplified by nitrogen, phosphorus and potassium (NPK) fertilizer application, totalling ~2.6 million tons annually. This is two-thirds of the total NPK used by Punjab, Haryana and Rajasthan. The limits of groundwater sustainability are on display in AP, where the last five decades have resulted in the highest percentage (~9.6%) of dry wells in India (GOI, 2017). Smallholders around the world have explored a range of adaptive strategies to overcome drought risks (Morton, 2007), but, in south India, deeper tube wells and reservoir construction continue to be the dominant coping strategy (Figures S3 and S4). In fact, farmers in south India incur high costs for drilling deep tube wells that rely on rainfall every year to replenish the thin aquifer beneath; an aberration of which leads to crop losses and social risks (Maréchal, 2009; Taylor 2013). By contrast, farmers in north India extract the currently reliable but quickly dwindling static groundwater stored in the thick alluvial aquifers. Additionally, they are also protected by meltwater of the Himalayan glaciers that acts as a buffer to drought stress (including the 2002 mega drought) (Pritchard, 2017). These differences are reflected in the predominant rice growing area, characterized by a larger interannual variation in AP (south) than in WB (north) (Figure S7).

The persistent WTD decline and increasing number of dry wells in WB (Figure S5) is a reminder of how quickly fortunes can change. The 'Ganges water machine' idea in the 1970s (Revelle & Lakshminarayana, 1975) was primarily based on deliberate lowering of groundwater levels in the dry season to increase the monsoon season infiltration and thus water availability for subsequent irrigation. And, in the recent past, this region particularly, with its high yielding alluvial aquifer, was believed to have the potential to offset the effects of aquifer stress in northwest India (Gleeson et al., 2012). Even the 2011 policy that extended groundwater access to millions of farmers was also anticipated to usher in a new agricultural revolution (earning the 2012 World Food Prize) (Jha, 2017). Unfortunately, rice crop area has begun to shrink in WB (Figure S7) and

the impending stresses from policy changes (Table S1) suggest that sustainability in this region may be hampered by both depletion and arsenic contamination (Fendorf et al., 2010).

4. Summary and Conclusions

Drought-induced groundwater depletion has affected agriculture and society in other parts of the world (Rodell et al., 2018). Some regions attracting scientific attention because of serious impacts include southeast Australia (van Dijk et al., 2013), north China (Huang et al., 2015), and most of the Middle East countries (Joodaki et al., 2014). Nevertheless, the trajectory of sustainability challenges in India is roughly comparable to that in the US (Perrone & Jasechko, 2019; Russo & Lall, 2017; Scanlon et al., 2012). As in north India, groundwater extraction exceeding recharge in the central and southern High Plains Aquifer of the US has caused steady WTD declines for at least 70 years, though at a far slower rate (Scanlon et al., 2012). As in south India, California's Central Valley is prone to drought, leading to dry wells and deeper drilling (Perrone & Jasechko, 2019). The unsustainable practice of deeper well drilling in the US is at least limited by socioeconomic conditions, aquifer thickness, and groundwater quality (Perrone & Jasechko, 2019). Moreover, major droughts have in some cases prompted reform and policymaking to improve water management (He et al., 2019). However, in India, the challenge is daunting because the livelihood of millions of smallholder farmers depends absolutely on groundwater-fed agriculture. Without the provision of subsidized farm power, the exorbitant cost of cultivation would have either left the land fallow and raised unemployment, or the prices of agricultural commodities would have soared. This would have pushed the society into an unimaginable new equilibrium. In both India and the US, the asymmetric responses of shallow versus deep wells and their sensitivity to the spatiotemporal scale of analysis (Alley et al., 2018; Russo & Lall, 2017; Scanlon et al., 2012) emphasize the need for careful interpretation.

India ranks second in the world in terms of greening, accelerated mainly through increases in multiple cropping since 2000 (Chen et al., 2019). Our study shows how the human exploitation of aquifers associated with that greening produces multiple sustainability challenges. Sustainable groundwater pumping is limited by the rate of recharge, and that, in turn, is likely to be modulated by climate change (Huang et al., 2016; Taylor et al., 2013). Despite being recognized as economically and environmentally unsustainable, dry season rice production is the largest consumer of groundwater in India. The eventual necessity of replacing dry-season rice production with that of alternate cereals seems unavoidable. However, rice is the staple food and livelihood of a large population in India, making its replacement difficult to imagine. While Odisha serves as a model for forest restoration, which can be referred to as 'avoiding the unmanageable' (Bierbaum et al., 2007), efficient water-use methods, solar powered micro-irrigation systems, and conservation agriculture, which have shown benefits over the current practice of intensification (Jat et al., 2020; Shah et al., 2018), should form the basis of 'managing the unavoidable'.

Indeed, divergent aspects of groundwater irrigation in north versus south India described in this study helped to explain the contrasting socioeconomic conditions unfolded in recent years. However, we recognize the main caveat associated with such regional comparison basically stems from the high hydrogeological and hydroclimatic differences that India is endowed with. We pointed out the hydrogeological variability within and between states from the policy implementation perspective. But from the hydroclimatic configuration, according to the Köppen-

Geiger climate classification (Beck et al., 2018), parts of northwest and south India represent the arid and semi-arid climate, in contrast to the tropical wet-dry and sub-tropical humid climate of central and northeast India, respectively. Thus, water requirement of growing even the same crop is constrained by hydroclimatic differences, which may also have introduced uncertainty. Interestingly, heterogeneity is also observed within the same hydrogeological and hydroclimatic region of northwest India, depending on the depositional architecture of the alluvial stratigraphy (Joshi et al., 2021; van Dijk et al., 2016a,b). These are the reasons why a detailed and nuanced analysis is so important to understand aquifer heterogeneity and ensure sustainable groundwater management. This can only be undertaken at the sub-regional to local scale worldwide (Aeschbach-Hertig & Gleeson, 2012). Nevertheless, in India, the framework presented for the northwest's depleted aquifer (Joshi et al., 2021; van Dijk et al., 2016a,b) is crucial to formulate location-specific groundwater resource management policies. This should be the benchmark for the proposed second green revolution in the eastern parts of India. In south India, innovative surface water management approaches, such as filling abandoned tanks during wet periods or inter-basin water transfer, may also partly offset aquifer stress. Importantly, a uniform depth of drilling policy would serve to narrow the socioeconomic gap between smallholders and rich farmers who can more readily absorb the drought shocks and afford multiple new deep wells.

Data Availability Statement

Data sets used in this study are obtained from open sources and government agencies. For example, the in-situ groundwater level data can be accessed from India water resources information system (https://indiawris.gov.in/wris/#/groundWater). Similarly, the minor irrigation census data is available in the form of published census report (http://164.100.229.38/sites/default/files/5th-MICensusReport.pdf). The primary agricultural data used in this analysis can be accessed from the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) and their Village Dynamics in South Asia (VDSA) database (http://vdsa.icrisat.ac.in/vdsa-requestData.aspx). But the users need to register first and then can accesss the macro-meso data that contains district scale land use data. The gridded rainfall and temperature data are procured from the Indian Meteorological Department (IMD). The datasets of Global Land Evaporation Amsterdam Model (GLEAM; https://www.gleam.eu/#downloads) and the standardized precipitation evapotranspiration index (SPEI; https://spei.csic.es/spei_database/#map_name=spei01#map_position=1415) are publicly available. The CSR GRACE RL05 mascon solutions (http://www2.csr.utexas.edu/grace/RL05_mascons.html) and the soil moisture from four land surface models (VIC, CLM, NOAH, MOSAIC) of NASA's Global Land Data Assimilation System (GLDAS) (https://disc.gsfc.nasa.gov/datasets?keywords=GLDAS) used in this study are also available at their dedicated websites. Indeed, we acknowledge AGU's data policy. But, for the data from IMD, we have given undertaking not to share. Yet, researchers can procure those data following the procedures given in their website (https://cdsp.imdpune.gov.in/).

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Figure Titles

Figure 1. Interlinkage of groundwater irrigation, climate and depletions in India based on (a) the map of percentage of land area equipped for groundwater irrigation (GWI), from the latest Global Map of Irrigation Areas (GMIA), (b) the aridity index (AI, ratio of annual rainfall to potential evapotranspiration) and (c) district scale groundwater development (GD, stress indicator pointing the percentage of annual extraction with respect to available resource from recharge). (d) Trends from GRACE records during 2002-2016 and its comparison with that from district-averaged in-situ water table depth (WTD) (represented by centroids) during (e) 1996-2016 and (f) 2002-2016. The states compared critically, AP, WB and Odisha, are shown.

Figure 2. Map of trends (inset, cm/yr) in the state-averaged mean WTD during (a) 1996-2016 and (b) 2002-2016. The maps (c)-(d) are same as (a)-(b), but for the 90th percentile. The states pointed in the maps are: Andhra Pradesh (AP), Tamil Nadu (TN), Karnataka (KA), Punjab (PJ), Haryana (HR), Rajasthan (RJ), West Bengal (WB), Odisha (OD), Gujarat (GJ), Uttar Pradesh (UP), Madhya Pradesh (MP), Maharashtra (MS), Kerala (KL), Bihar (BR), Jharkhand (JH), Chhattisgarh (CG).

Figure 3. Temporal and vertical description of WTD, smoothed with the LOWESS regression and shaded with the 95% confidence interval, based on the 25th percentile (P25), mean, 75th percentile (P75), and 90th percentile (P90) of data for the representative states of India.

Figure 4. Timeline of major farm power and other policies associated with groundwater irrigation in (a) Andhra Pradesh (AP) and (b)West Bengal (WB) since the 1970s. Horizontal lines represent the broad periods and vertical lines for year of policy implementation.

Figure 5. Transitions in human-natural system in AP through (a) irrigated area in response to changes in (b) rainfall and (c) streamflow since the 1970s. (d) The corresponding land-use change (LUC) for water-intensive crops. The marked years (in cyan) represent the 2002-2004 dryness that prompted the free farm-power policy. The LOWESS regression reflects the temporal evolution.

Figure 6. Hydroclimatic linkages based on (a) the standardized seasonal (i.e., August, November, January and May) WTD (LOWESS regression shown) in subregions of AP (Telangana (TG), Rayalaseema (RS) and coastal AP (CAP)), West Bengal (WB) and Odisha (OD), and (b) the corresponding the 12-month SPEI (standardized precipitation-evapotranspiration index) expressed through (c) The non-monsoon summer season (March-April-May, MAM) 15, 30 and 45-day minimum streamflow at the Godavari basin outlet, essentially sustained by baseflow, are largely affected by the human-modified droughts. (d) The seasonal terrestrial water storage (TWS) anomalies since 2002 consistently captures the differential aquifer response.

Figure 7. Empirical orthogonal function (EOF) analysis of the seasonal (monsoon, post-monsoon, winter, summer) WTD during 1996-2016 shows (a) the leading mode (EOF1) of variability and (b) the corresponding principal component (PC1). (c)-(d) same as (a)-(b), but for the second mode (EOF2) and PC2. (e) Impact of the Indian Ocean SST on groundwater levels reflected through the spatial distribution of correlation coefficients between PC1 and SST over Indian Ocean and (f) through the time series of seasonal SST over western Indian Ocean.

[Earth's Future]

Supporting Information for

Groundwater variability across India, under contrasting human and natural conditions

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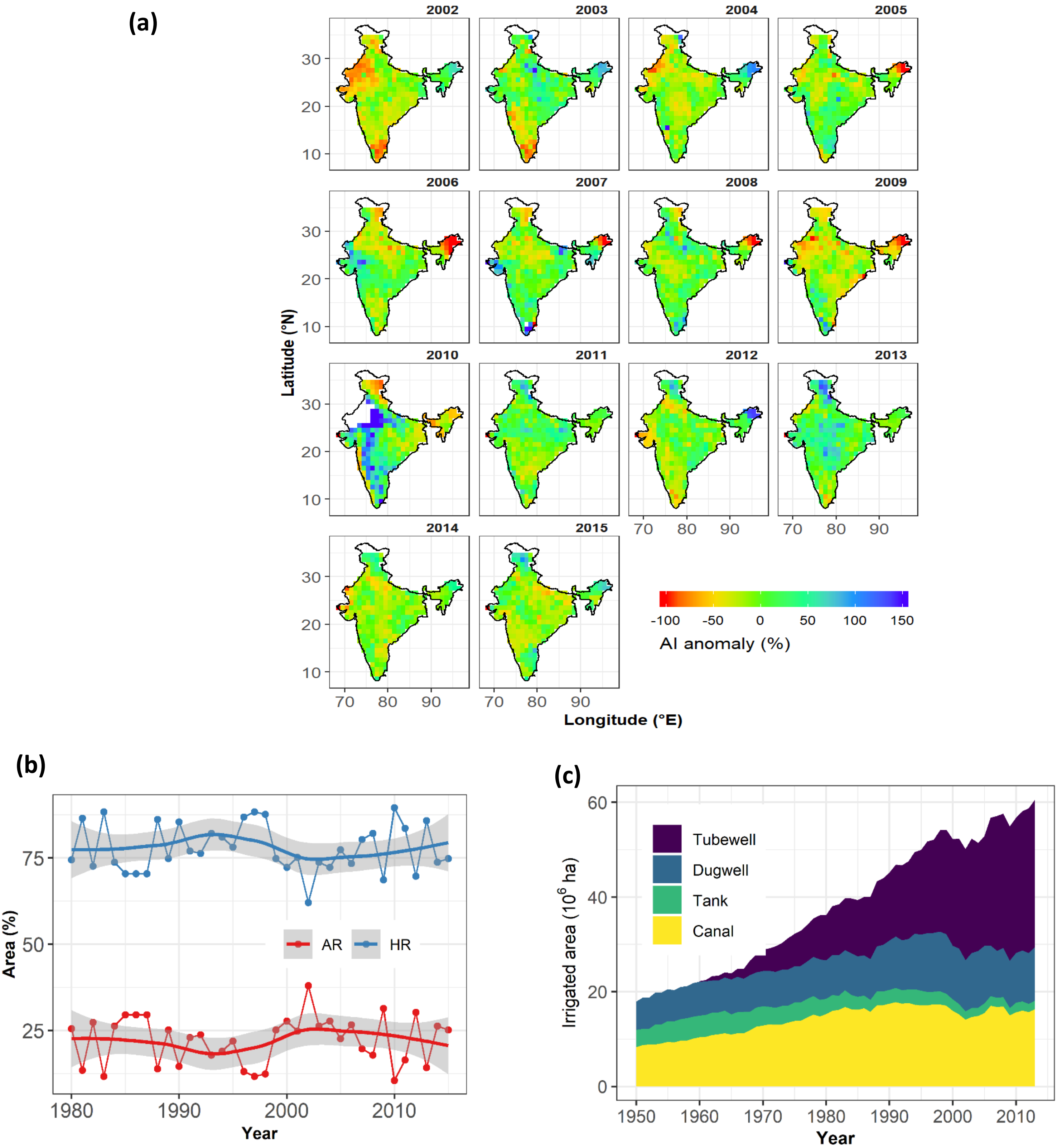


Figure S1. (a) Spatial distribution of the aridity index anomalies (from the 1980-2000 mean) since the 2002 major drought. (b) Rising percentage of India's landmass under arid region (AR, AI <0.65) at the cost of humid region (HR, AI ≥0.65) since 1980, smoothed with the LOWESS regression and shaded with the 95% confidence interval. (c) This is the primary reason of a spectacular rise of groundwater irrigated area as surface water irrigation stabilized and declined since 2000.

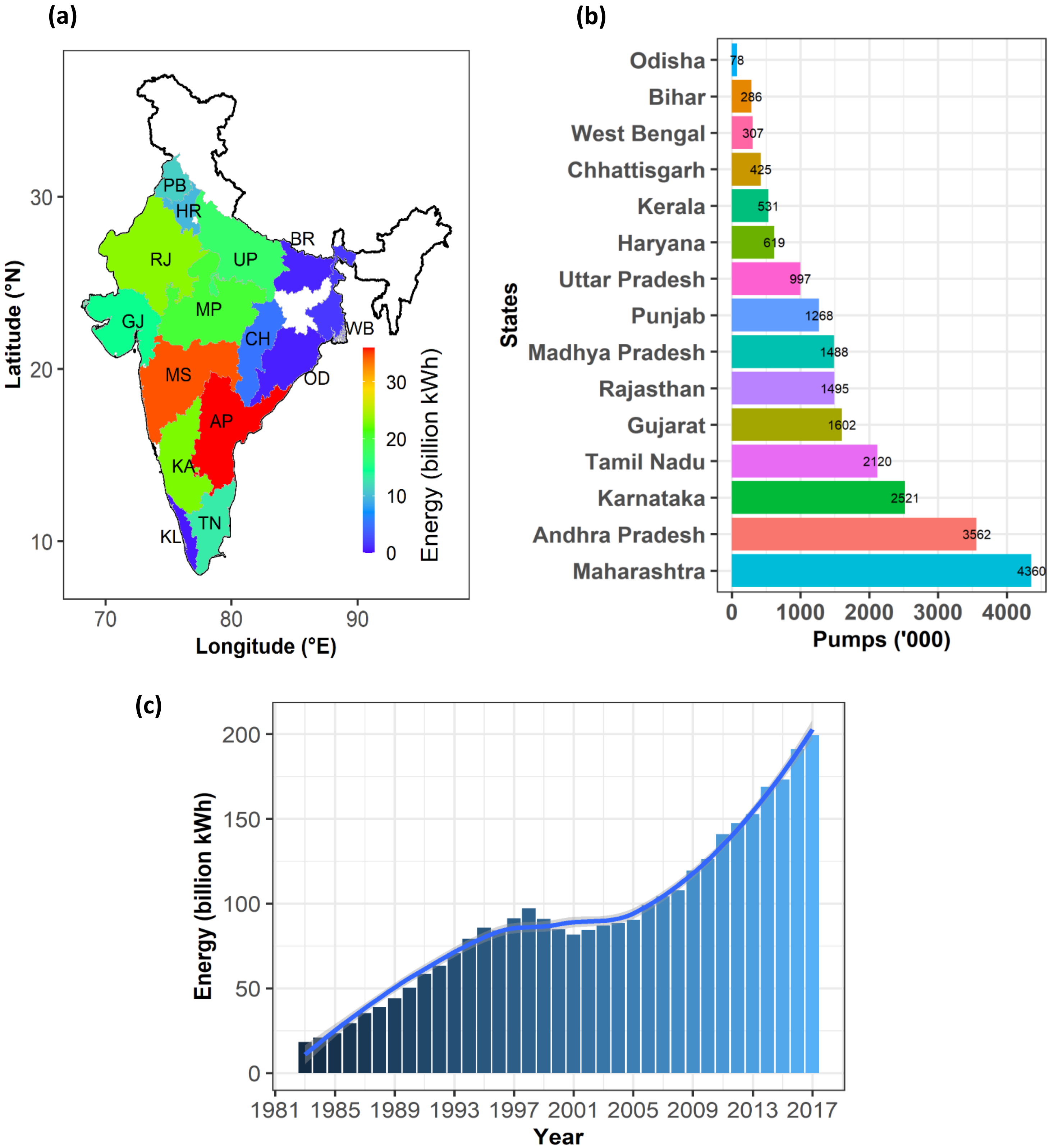
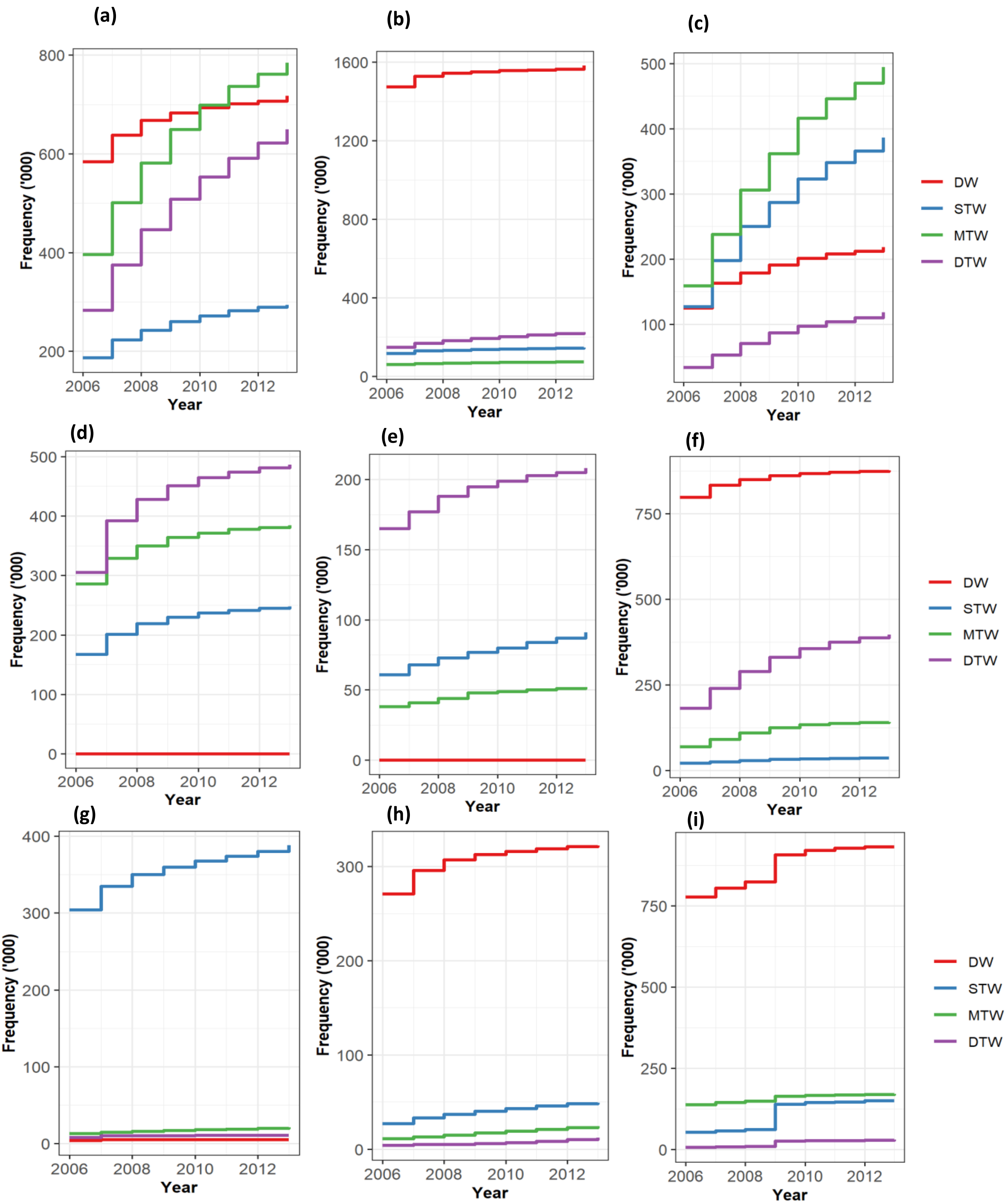


Figure S2. Energy use for agriculture in India. (a)-(b) state-scale distribution of energy consumed matching the pumps employed for extraction of groundwater. (c) Steady growth in energy consumption since the 1980s, being slumped around early the 2000s. The states pointed in (a) are: Andhra Pradesh (AP), Tamil Nadu (TN), Karnataka (KA), Punjab (PJ), Haryana (HR), Rajasthan (RJ), West Bengal (WB), Odisha (OD), Gujarat (GJ), Uttar Pradesh (UP), Madhya Pradesh (MP), Maharashtra (MS), Kerala (KL), Bihar (BR) and Chhattisgarh (CG)



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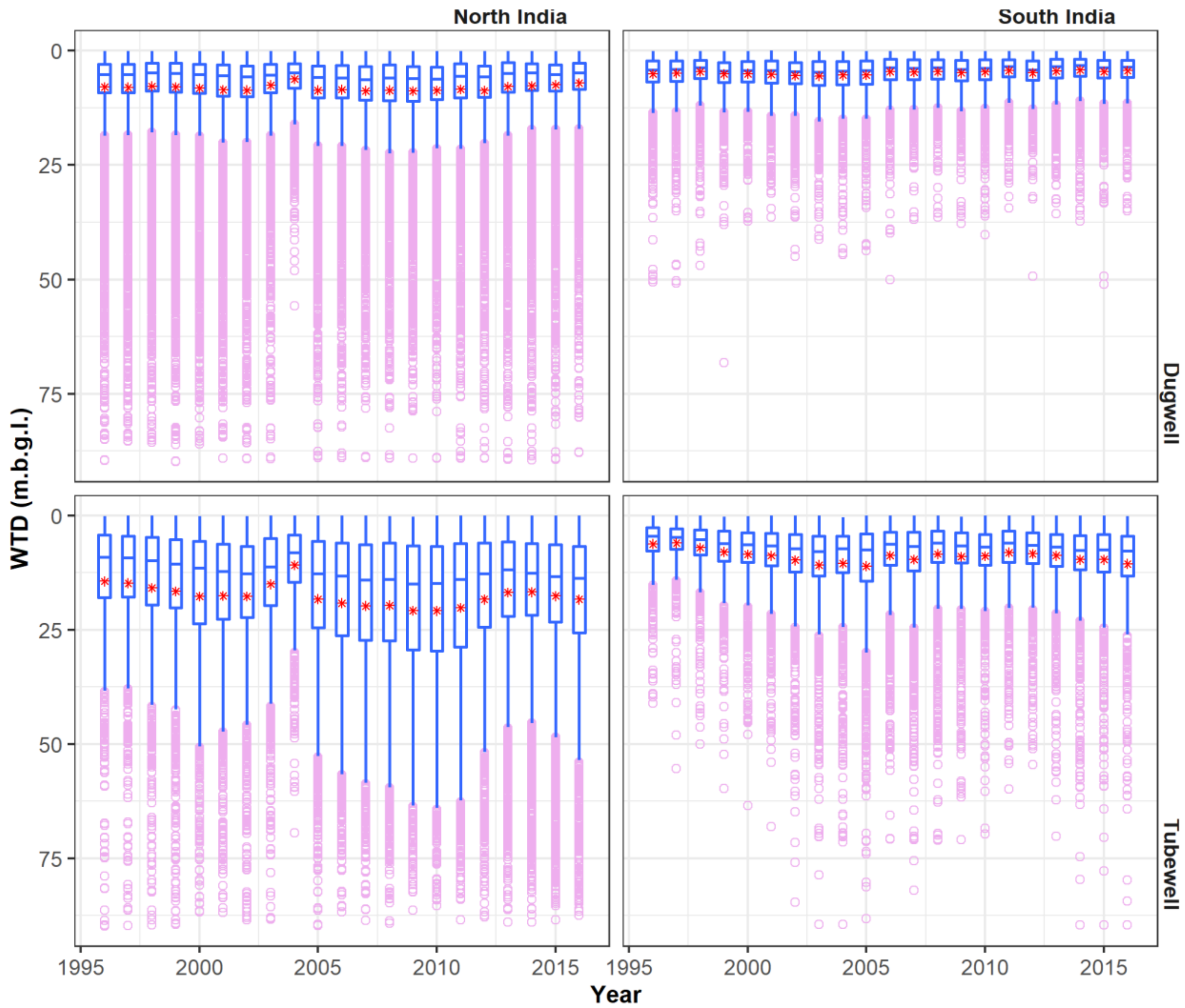
(a)



(b)

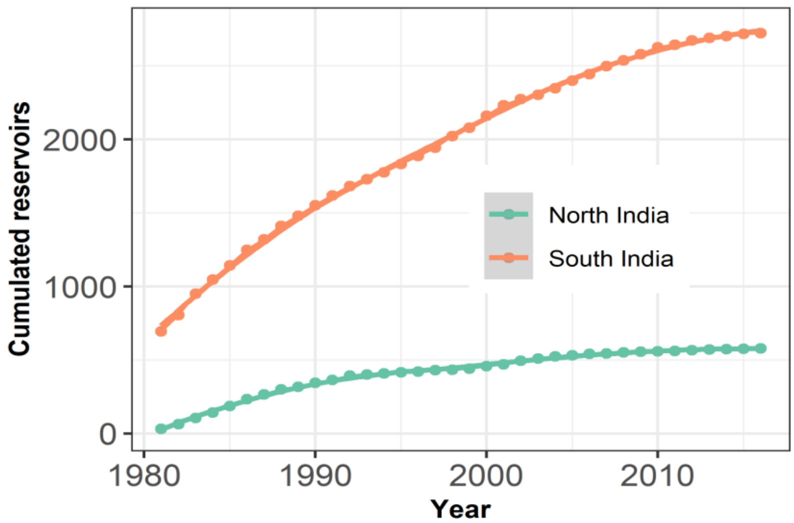


Figure S4. (a) Boxplots describing the regional distinction of groundwater levels between north (above 23º N) and south (below 23º N) India with respect to dugwell and tubewell (shallow and deep bore wells) during 1996-2016. In the box, representing the interquartile range (P75-P25), the horizontal line and red astric indicate median and mean of WTD, respectively. Pink circles indicate values exceeding 1.5× interquartile range which appears to have influenced the mean and percentiles of WTD. (b) Contrasting growth of reservoirs in north and south India constructed during 1981-2016.

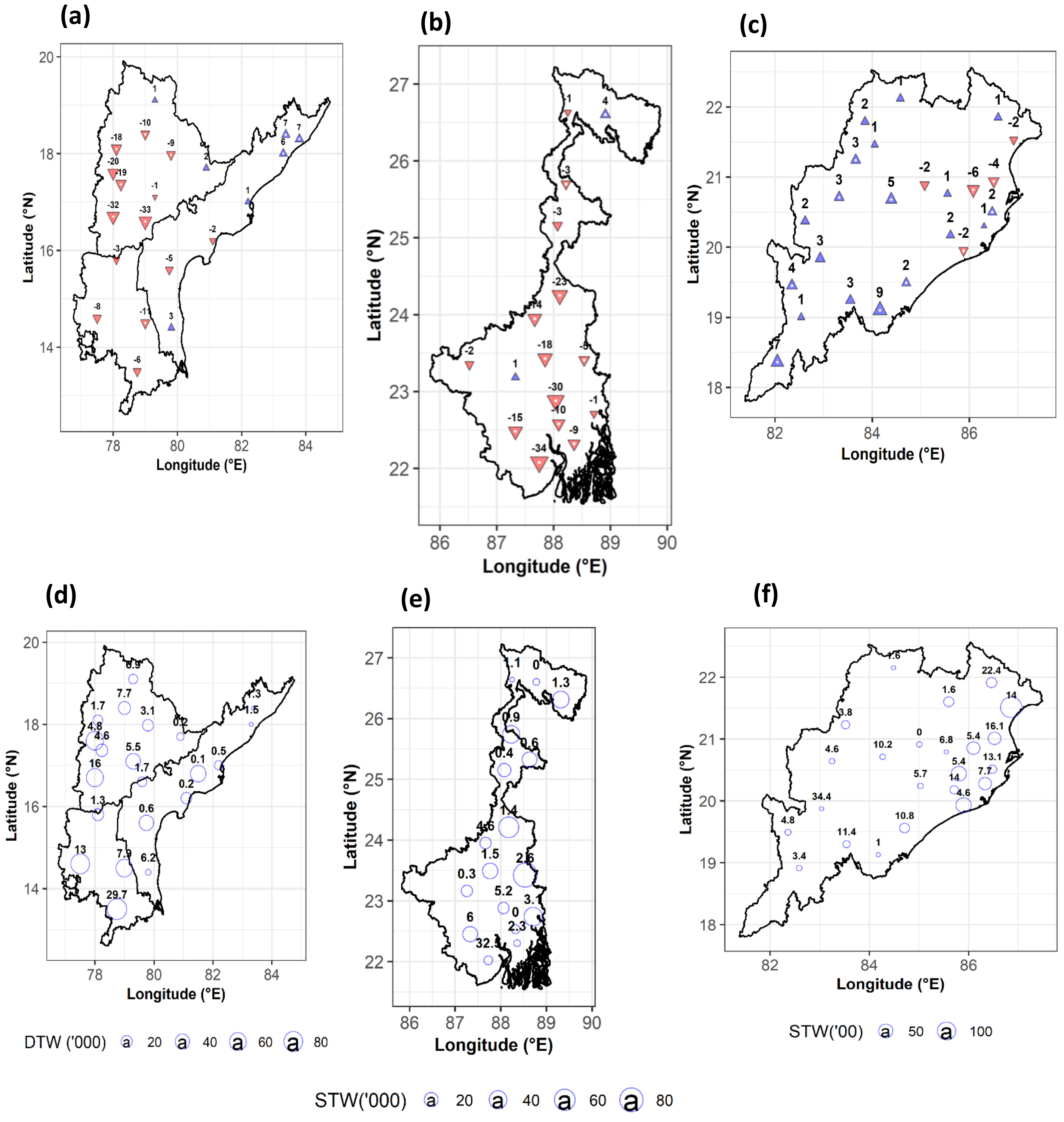


Figure S5. Drying of wells in response to WTD trends (cm/yr, inset values) during 1996-2016 for the states of (a) AP, (b) WB and (c) Odisha. Triangles (inverted) with dots represent the districts experiencing significant (p<0.05) rises (declines). The corresponding frequency of (d) deep tubewell (DTW, in thousands according to the size of circles) in AP, (e) shallow tubewell (STW, in thousands) in WB and (f) shallow tubewell (STW, in hundreds) in Odisha, based on the minor irrigation census. The inset values represent the percentage of dry or defunct wells.

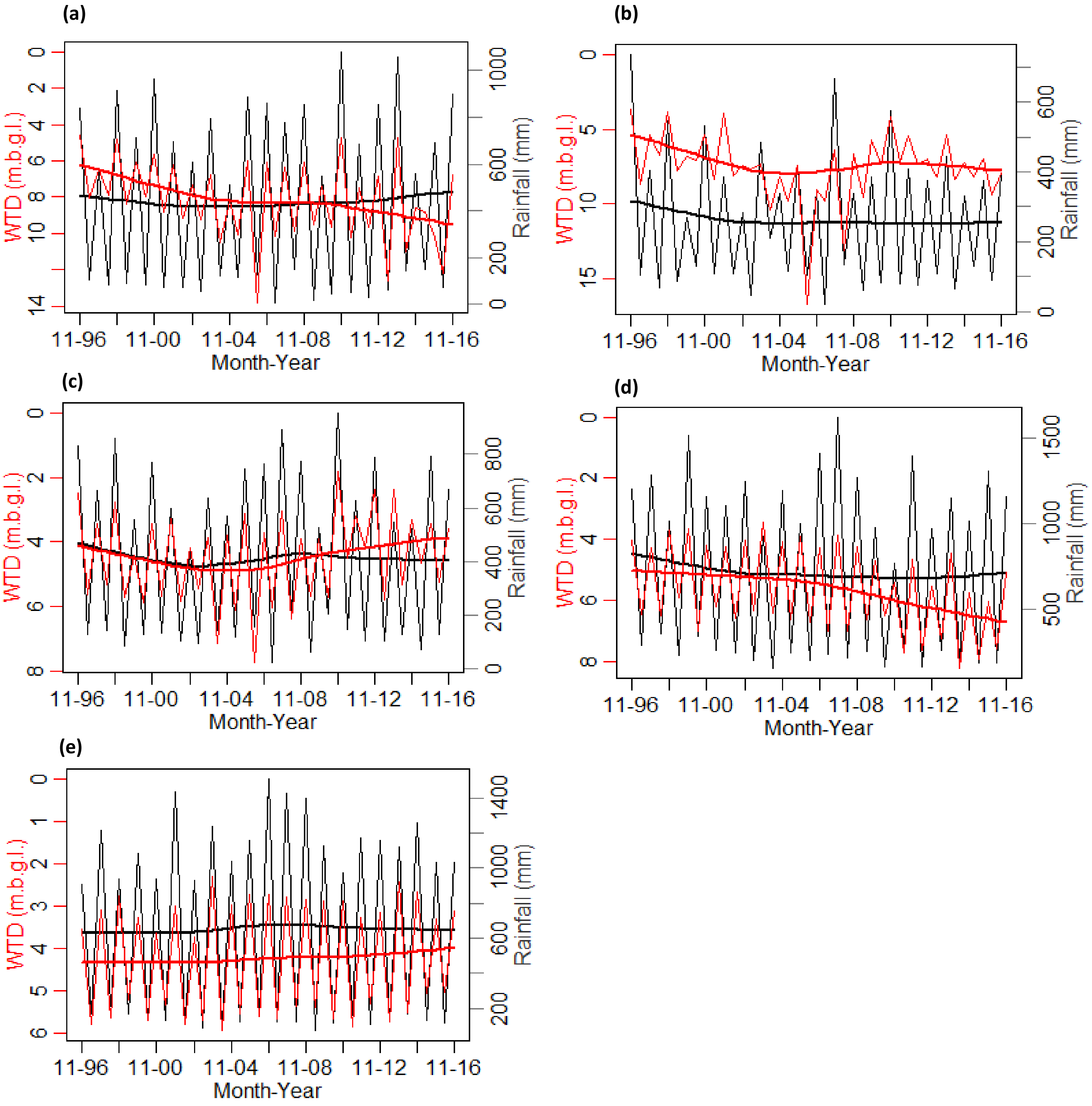
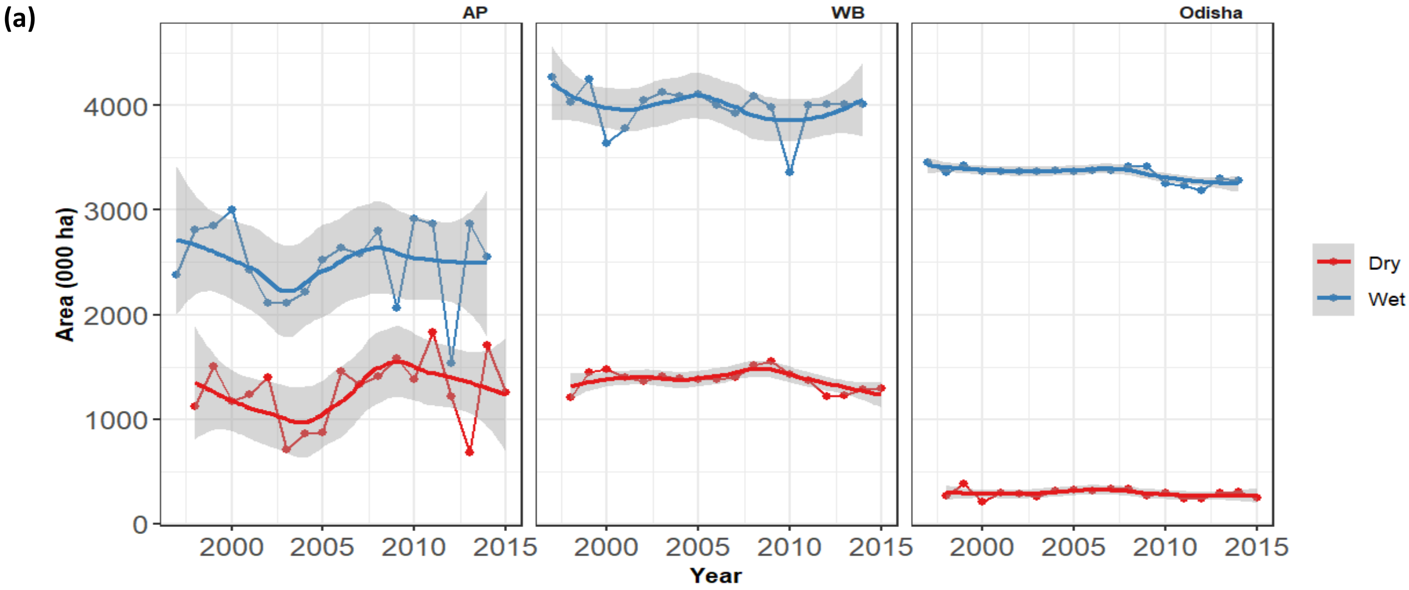


Figure S6. WTD (m below ground level) in the post-monsoon (November) and pre-monsoon (May) seasons during 1996-2016 and their association with the monsoon and pre-monsoon rainfall modelled through the vector autoregression (VAR) for the sub-region (a) Telengana (TG), (b) Rayalseema (RS) and (c) the coastal part (CAP) in AP, (d) WB and (e) Odisha. The VAR model parameters and performance measures are presented in Table S2.



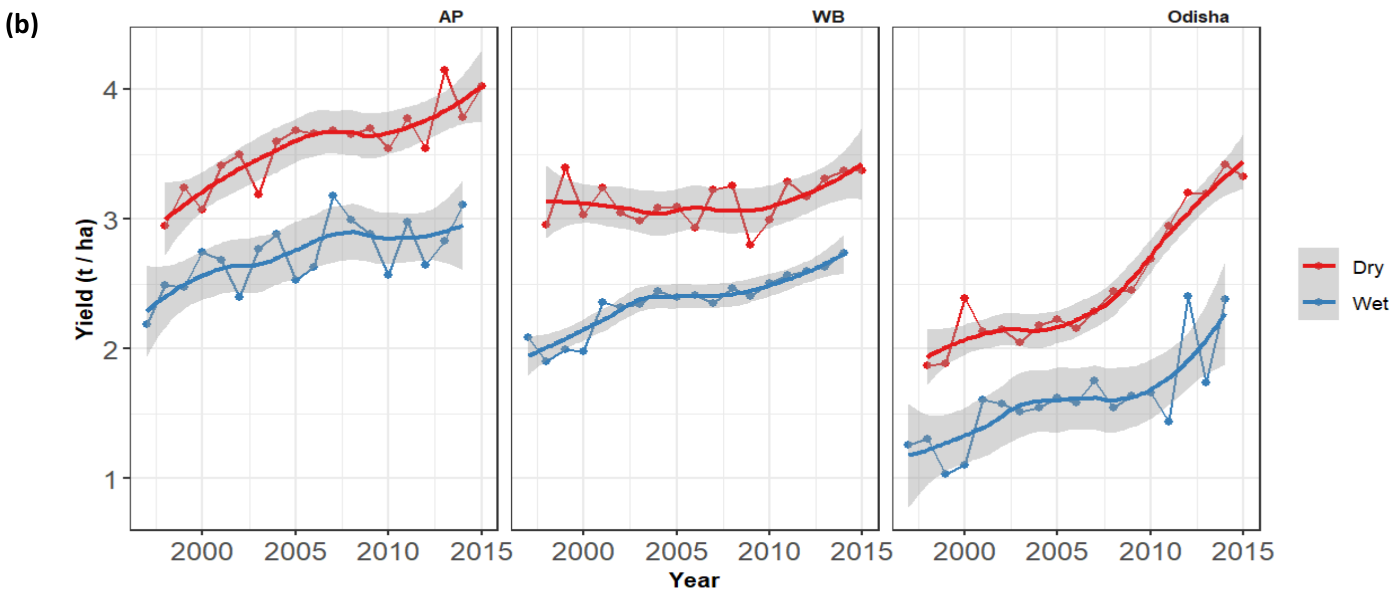


Figure S7. Temporal changes in rice cultivation (major land-use) with respect to (a) Area (thousand ha) under the dry (summer) and wet (monsoon) season rice in AP, WB and Odisha. (b) same as (a), but for yield (tons/ha). The LOWESS regression, along with the shaded 95% confidence interval, indicates the dominant patterns and turning points.

Table S1. Chronology of policies related to groundwater irrigation in Andhra Pradesh (AP) and West Bengal (WB)

Period	Policy description
	Andhra Pradesh (AP)
Metered power	• During the early 1970s, when groundwater irrigation galvanized in the northern alluvial aquifer along with the unset of the Green Revolution, most of the southern hard rock regions was irrigated through the pre-independent era gravity-flow surface irrigation systems. The architect of most of these structures, Sir Arthur Cotton (https://thewire.in/agriculture/british-general-master-irrigation), is still revered for the societal benefits, and the world-class structure in the Godavari is popularly known as 'Cotton Bridge'. Surface irrigation transformed the barren hard rocks (weathered granitic basement) of AP under semi-arid climate into prospering agricultural ecosystems, known as the 'rice bowl of India', notwithstanding its impact to the global human water footprint (Jaramillo & Destouni, 2015). For whatever limited groundwater irrigation, possibly due to less rural electrification, power consumption was metered, like domestic use.
Subsidized power	• The political orientation of groundwater irrigation, for the first time in India, initiated in AP in the form of 'flat power tariff' as an election promise in 1977 (Dubash and Rajan 2001). This policy was then implemented in other states because of socio-political compulsions and comparisons. Thereafter, subsidization based on economic condition was implemented in 1983 and then the pump capacity (horsepower) based tariff.
Economic reform	• Although the World Bank supported the power reform started since 1991 as a part of the economic reform and emphasized tariff modifications (World Bank, 2004), it could not be materialized due to farmers' protest and political challenges. Using the rhetoric 'free power is no power', the tariff was hiked in 1999 to ensure quality power supply. • To arrest the large-scale declines and sustain aquifer, the government passed the Water, Land and Trees Act (WALTA) in 2002, which required registering the existing tubewell and permission to dig new ones. But then a spell of drought and heat altogether changed the course of groundwater irrigation. It is reported that about 1 million tube wells were sunk during 2000-2003 without even realizing any additional irrigation area (Kumar et al., 2011). The role of rural banking facilities in the tubewell revolution that expanded under the economic reform process cannot be discounted (Burgess and Pande, 2005).

Free power	• In 2004, the free-power policy was implemented, along with the waiver of previous tariff arrears. This decision was defended as an ‘emergency response to an ‘emergency crisis’ that claimed roughly 3,000 human lives, mostly the suicides of the smallholders (Birner and Sharma, 2015). In 2011, a flash drought that coincided with the critical irrigation requirement of crop transformed into a social crisis akin to that of the 2004 (DTE, 2015). Worsened further by the multiyear drought during 2014-2016 that prompted sinking of ~3.2 million additional tubewells. • Thus, in 2016, the NTR Jala Siri project was implemented to assist poor smallholders in the drought prone areas by drilling bore wells. In fact, the proliferation of deep wells facilitated by free power is evident from the government’s socioeconomic survey reports indicating pump set connections and expenditure, which is far more than registered wells shown by the minor irrigation census report. • Ineffectiveness of the WALTA Act that restrict deep wells is extensively highlighted in media reports (DTE, 2015). Of course, the social crisis (mainly farmers suicide) in AP drew considerable international attention, stimulating implementation of several collaborative projects (involving the UN-FAO, World Bank, CGIR-ICRISAT and others) in the most affected districts (Garduño et al., 2009). Even the UN-FAO intervention has been referred as ‘the first example globally of large-scale success in groundwater management by communities’ (Garduño et al., 2009). Resource conservation through programs, such as the National Solar Mission and Mission Kakatiya (to rejuvenate tanks) were implemented (Kumar et al., 2016). But their long-term impacts appear to be outweighed by drought and deep well drilling, even in districts where most of the conservation works were focused (Fosli, 2014). • Unfortunately, in 2019, the duration of free power was raised, from 7 to 9 hours in AP (new) and to 24 hours in Telengana (segregated from AP since 2014). However, farmers, facing ultimately the dire consequences of rampant well failures, expressed serious concern over aquifer sustainability (BBC, 2019).

West Bengal (WB)

Diesel-powered	• Until the tenants secured higher security over tenure through the land tenancy reform ‘Operation Barga’ during the late 1970s, the agriculture productivity in WB was the lowest, and thereafter it rose steadily, stimulated mainly by groundwater irrigation. Diesel-powered pumps dominated (more than 85%) during the 1980s, largely because of the shallow aquifer, lack of rural electrification and high cost of connection.

Flat tariff	• As shallow wells rose, flat tariff was introduced since 1991, because transaction cost of bill collection increased substantially compared to the revenue generated from meter reading. It also encouraged the rural rich to expand irrigation by selling water to small holders having fragmented land structure. • Depletion of groundwater resources due to flat tariff and thus the increased arsenic infestation, even in the food chain, prompted the West Bengal Groundwater Resources (Management, Control and Regulation) Act 2005, which needed the government's permission to sink wells.
Metered power	• As a part of energy sector reform and also to raise water use efficiency and make water markets more competitive, the metered power policy was introduced in 2008. It is again seen to be beneficial to rich pump owners who will pay less but charge more for water selling.
License abolition	• Due to stagnation in agricultural growth in the 2000s, mainly because of droughts, the 2005 Act was amended in 2011, facilitating greater groundwater access to hundreds of thousands of smallholder who were deprived of license for several reasons. Moreover, cost of electricity connections to pumps were reduced through subsidization. These measures were dubbed as a stepping stone to kick start a second green revolution. • In order to tackle crop failure during the recent droughts, the government has undertaken a populist policy 'Sech-Bandhu Prakalpa' in 2014 that provides pump sets with power connectivity (https://wb.gov.in/government-schemes-details-sechbandhu.aspx). • But the impact assessment of the consequent spur in electrification and well revolution, supported in part by private investments, raises logical concerns over the future sustainability since economic benefit is not notable (Buisson, 2015; Mukherji et al., 2018).

Table S2. Response of WTD to rainfall (log transformed) using vector autoregressive (VAR) model

Region	Variable	Coefficient	Std. Err.	P-val	F-cal	R^2
TG	WTD_{t-1}	-0.27	0.15	0.08	25.44	0.66
	$Rainfall_{t-1}$	0.95	0.24	0.00		
	Constant	3.78	2.25	0.10		
	Trend	0.08	0.02	0.00		
RS	WTD_{t-1}	0.34	0.15	0.03	8.45	0.37
	$Rainfall_{t-1}$	2.03	0.41	0.00		
	Constant	-5.98	2.95	0.05		
	Trend	0.02	0.03	0.43		
CAP	WTD_{t-1}	-0.16	0.17	0.36	22.62	0.66
	$Rainfall_{t-1}$	0.95	0.25	0.00		
	Constant	0.46	2.18	0.84		
	Trend	-0.02	0.01	0.06		
WB	WTD_{t-1}	-0.19	0.16	0.24	87.19	0.87
	$Rainfall_{t-1}$	1.16	0.24	0.00		
	Constant	-1.78	2.27	0.44		
	Trend	0.06	0.01	0.00		
Odisha	WTD_{t-1}	-0.43	0.17	0.01	179	0.93
	$Rainfall_{t-1}$	0.63	0.20	0.00		
	Constant	2.52	1.90	0.19		
	Trend	-0.01	0.01	0.11		